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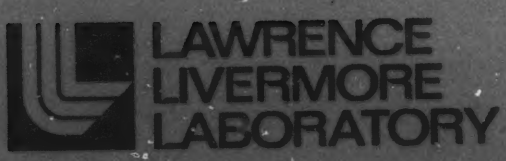
Subsystem Response Review

Seismic Safety Margins Research Program

J. Fogelquist, M. K. Kaul, R. Koppe, S. W. Tagart, Jr., H. Thailer, R. Uffer
Nuclear Services Corporation

Prepared for
U.S. Nuclear Regulatory Commission



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ABSTRACT

This report discusses and makes recommendations on the current status of subsystem seismic evaluation techniques and uncertainties in Nuclear Power Plant design. A classification system is developed in order to fit subsystems into similar, more manageable groups. Various methods of subsystem evaluations are discussed and significant differences are pointed out. In order to quantify the uncertainties in subsystem analysis, questionnaires were sent to a number of experienced industry experts who assigned uncertainty probabilities to different catagories of subsystems.

ACKNOWLEDGEMENT AND DISCLAIMER

The views expressed in this report are conclusions reached by the authors and do not necessarily represent conclusions either by Lawrence Livermore Laboratories nor industry experts who were solicited for the questionnaire.

The authors wish to thank the generous support of those industry seismic experts who participated in the response to the questionnaire. Their names are listed in Appendix B.

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1.0 INTRODUCTION

This project is directed toward a portion of the Seismic Safety Margins Research Program which includes one link in the seismic methodology chain. The link addressed here is the structural subsystem dynamic response which consists of those components and systems whose behavior is often determined decoupled from the major structural response. Typically the mathematical model utilized for the major structural response will include only the mass effects of the subsystem and the main model is used to produce the support motion inputs for subsystem seismic qualification.

The main questions addressed in this report have to do with the seismic response uncertainty of safety-related components or equipment whose seismic qualification is performed by a) analysis, b) tests, or c) combinations of analysis and tests, and where the seismic input is assumed to have no uncertainty. In order to strike a balance between a generic treatment of subsystem response uncertainty and a more specific treatment of detail problems which are unique to certain pieces of equipment, a typical LWR subsystem inventory has been developed for BWR and PWR reactor systems. This inventory has been used to help classify a limited number of sets of components with common seismic uncertainty characteristics suitable for use in the Phase 1 SSMRP effort. The uncertainties of seismic response are quantified through judgment probability assignments by experienced NSC personnel as well as informal inputs from selected seismic nuclear experts within the industry.

As a part of this review, the methods of seismic qualification are summarized. Most of these methods are in a state of continuous evolution and suggestions are made for further improvements.

2.0 SUMMARY AND CONCLUSIONS

Subsystem response uncertainty has been characterized by use of a dimensionless K factor (the ratio of actual seismic response to predicted seismic response). This K factor has been treated as a random variable in order to define quantitative degrees of conservatism, non-conservatism, separation of random and modeling uncertainty, and non-linear effects. The K factor approach appears to meet the project objectives of simplifying the subsystem response uncertainty for use in the Phase 1 SSMRP effort.

In order to formalize the procedure of quantifying K, a questionnaire was developed which requires six probability numbers to be assigned for each different class of subsystem of interest. Eighteen subsystem classes were defined and form the basis for accumulating all "prior probability data" ("prior probability data" in this report refers to the results of the questionnaire response by experts, in which each datum value represents a priori probability assignment in a Baysian sense. It is assumed that no specific experimental results are available to be used as a relevant statistic. The concept of using experts to generate synthetic data on the basis of judgement is not intended as a substitute for real data but only as a starting point to combine potential future experimental results with the prior probability assignments). These results are shown in Table 5.7.2, Averaged Results from Questionnaires. In view of the imprecise definition of the probability numbers gathered from the questionnaire, any suitable probability distribution consistent with the six probability numbers developed here would be acceptable. In this study, however, K as well as most of the underlying parameters has been assumed to be lognormally distributed. This is discussed further in Section 3.2. Analysis of this data showed that the subsystem response uncertainty can be represented by as few as three superset classifications wherein six probability numbers per superset can sufficiently quantify our current state of uncertainty of critical subsystem response. The results are shown in Table 5.7.2.2, Simplified Classification Scheme for

Phase I of SSMRP. It is shown in Section 5.7.3 how each individual cause of uncertainty can be separated from all others so that sensitivity studies important to Phase I of SSMRP can be easily carried out.

Further insight into the causes and analysis of subsystem response uncertainty would benefit from a quantitative treatment of subsystem transfer functions. The use of subsystem transfer functions even in an elementary form greatly increases the engineering and computation complexity of uncertainty propagation and would have questionable value for SSMRP unless a major experimental program were also undertaken as part of the Phase 2 program. The experimental program would be needed to supply a data base to supplement the judgment estimates developed in this report.

The methods of seismic qualification in use today, namely a) analysis, b) test, and c) combinations of analysis and test possess a common philosophical thread in that they all demand a conservative design procedure. However, when attempts were made to quantify the uncertainty involved in the typical procedures, it was clear that a common denominator for analysis and test qualification is lacking. The two procedures do not quantify the same dynamic characteristics of subsystems. In the case of analysis, the maximum primary stress is the parameter of dominant interest while in the case of test, the operability or lack of operability (a binary condition not related in a simple way to structural dynamics) is the chief concern. Suggestions are made for improvement in Section 3.3 of this report.

3.0 RECOMMENDATIONS

3.1 Subsystem Response Classification

A triad classification scheme has been developed using the following generic characterizations of seismic qualification.

1. Expected Dynamic Behavior.
2. Method of Seismic Qualification.
3. Response Parameter Used.

Through the use of this scheme, a typical LWR inventory consisting of approximately 140 different types of components can be reduced to 15 to 20 sets where uncertainty can be assigned to each set. A significant number of components will not exactly fit one of the 15 to 20 sets, but differences in uncertainty between the sets has been found to be smaller than the uncertainty within any one set. Therefore, no significant loss of information is expected for Phase 1 by placing the non-fitting components into one closely related set of the 18. Due to the large variation of prior probability assignments (see Section 2.0) within each of the 18 sets, and the minor differences between different sets for most of the 18, it is recommended that the number of groups be further reduced to about 3 to 5 groups for the purpose of the Phase 1 work. Such groupings are discussed in Section 5.7.2.

Although the development of 18 sets has been performed in this project, a specific plant inventory is recommended before the sets are finalized for the Phase 1 SSMRP evaluation. Such an inventory would serve two purposes: a) to make use of actual plant information to identify seismic qualification and parameters used, and b) to provide a checklist concerning the description and numbers of safety-related components involved in the actual plant including correlation with safety systems affected.

The typical procedures developed and described in Section 4.0 of this report should be used on the actual Zion plant subsystems.

3.2 SSMRP Subsystem Response Prediction for Phase 1

3.2.1 The Overall Subsystem Response Approach

The K factor uncertainty description developed in this report can be used in a sampling fashion to evaluate the response of all safety-related subsystems for the Phase I effort of SSMRP. The general nature of the K distribution is assumed log normal, and therefore it is recommended that a statistical fitting technique be used to provide the desired log normal parameters with prior type probability data gathered for this report and supplementary sources if available. The log normal distribution has the characteristic that it may be generated by a series of products

$$K = K_1 * K_2 * \cdots K_n \qquad (1)$$

where it can be shown that if the individual factors are log normal, then the product will also be log normal. This provides a convenient format to encode the uncertainty information for subsystem response where one overall factor K represents the uncertainty due to all (random and modeling) uncertainty, and any individual uncertainties can be identified by K_i factors which are also approximately log normal. While the main focus of this report has been the development of a data base for the overall K factor for each of 18 categories of safety-related subsystems, Section 5.7 illustrates a breakdown of the individual causes of uncertainty which makes up the overall K. This format makes a versatile treatment of subsystem response uncertainty possible for the Phase 1 SSMRP sensitivity effort. Further details are illustrated in Section 5.7.3.

3.2.2 The Transfer Function Approach

Reference 1 defined a set of two random variables, K_a and K_w which can be applied to the linear system transfer function in the following form

$$H'(w) = K_a * H\left(\frac{W}{K_w}\right) \qquad (1)$$

where

$H'(w)$ is the uncertain subsystem transfer function

$H(w)$ is the deterministic subsystem transfer function

The form of equation (1) implies a correlation of the types of uncertainty present which is not necessarily identical to that expected from a more realistic analysis of subsystem response, but the form does permit all types of subsystem uncertainty to be quantified in a more comprehensive way than that discussed in Section 3.2.1 of this report. The chief advantage of course is that the uncertainties of the seismic input can be separated from those of the subsystem itself.

The difficulty with this approach is that normaily the subsystem transfer functions are not available, and even if they were, several transfer functions are necessary to account for the three-dimensional propagation of seismic motion from the subsystem input points to obtain the total subsystem reponse.

Because there are thousands of different subsystems involved, this means that analysis complexity would grow to an unwieldly degree if attempts were made to incorporate this approach into the overall SSMRP computation scheme. However, the correlated transfer function uncertainty approach may still be useful during Phase 1 of SSMRP to better understand uncertainty propagation in simplified dynamic models. For this reason it is recommended that some consideration

be given to further develop this approach so that results can be compared with the results of the overall K factor approach. See Appendix C for further details of the transfer function approach.

3.3 Possible Subsystem Response Improvements (Generic)

Some suggestions are made for areas of improvement in subsystem seismic response of a generic nature. They are identified as follows not necessarily in their order of importance.

3.3.1 Composite Response-Fragility Parameters

Since the main objective for seismic response prediction is to provide numerical values that will indicate proximity to component failure, it is natural to question whether the best parameters are being used today to measure the response. The maximum primary stress is the single most used parameter, but it is well known that fragility involves more complex quantities than the maximum primary stress. For example, fatigue or combined ratcheting and fatigue are probably equal to, if not more important, than maximum primary stress in quantitively understanding dynamic failure of most metal structures. In addition, since electrical or electro-mechanical components are also of direct concern, the type of dynamic motion which contributes to their failure is quite uncertain. The idea of developing a composite response-fragility parameter to measure seismic severity has been discussed in Reference 2. In order to develop an improved parameter or parameters, considerable experimental studies would need to be performed, but it appears likely that improvements in this area are capable of improving the state of information on subsystem performance.

3.3.2 Dynamic Plastic Methods

Since a large source of conservatism and uncertainty in subsystem dynamic response prediction and fragility results from ignoring the

effects of possible nonlinearities, this is a likely area for further methods development. Some efforts have been undertaken in this area (Reference 3), but considerably more work is needed before non-linear effects can be economically assessed and accounted for in the analysis and design of subsystems. It is necessary to exploit simplified computation methods or possibly even equivalent linear methods. This area holds much promise for increased understanding of seismic margin of subsystems.

3.3.3 Relate Seismic Margin and Load Combinations

Both the seismic dynamic response problem and the general load combination problem (static and dynamic) are highly interrelated. Structures and components always fail as a result of some combined environmental and loading conditions. Generally as the loading conditions approach failure states, the response and fragility behavior are highly nonlinear. It is necessary to perform experimental and theoretical development so that improved design rules can be developed which address this problem.

3.3.4 Develop Improved Piping Dynamic Response Methods

Since piping is such a major portion of seismic qualification, much improvement in seismic design would be accomplished if methods could be developed and qualified which are realistic and yet not too expensive. This would involve addressing the problems related to multiple input support motions, non-linearity, closely spaced mode effects, primary versus secondary stress effects and support behavior. The problems associated with the more rigid behavior near supports need to be better addressed (Reference 4). Unless the total number of modes considered in the analysis include the modes associated with the mass points near the support, the computed response especially near the points of support can be significantly in error. This is true for response spectrum method of analysis as well as for time-history modal analysis. Similar (but of smaller

order of magnitude) inaccuracy may also creep into direct-integration time-history analysis if the integration time-step is not small enough with respect to the period of modes associated with the mass points near the supports. In comparison, however, this error due to the inclusion of insufficient number of modes is more critical while computing acceleration response of points near the supports by response spectrum method, unless the computed responses are adjusted so that the mass points very near the support have accelerations nearly equal to the input support accelerations, and not nearly zero acceleration.

3.3.5 Relating Test Methods with Analysis Methods

Since analysis methods and test methods for seismic qualification are to some degree interchangeable, it is desirable to develop a common basis for both. For example, in analysis qualification certain margins of design are implicit due to the stress criteria used, while when testing is used, no consistent margins are currently standardized. In addition, it would seem useful to be able to measure some common parameters in a test which could be more directly compared with what is done when analysis is used for seismic qualification. An example of such common parameters would be strain gage results in a structural cabinet where the chief parameters of interest may be specified in terms of shake table accelerations and resulting electrical component accelerations. This should address the problems of three-dimensional effects under test including the possible effects of rotations as well as translations. (See Section 5.2 for more detailed discussion.)

3.3.6 Develop a Seismic Probabilistic Risk Design Method

The SSMRP program would seem to be an ideal place to begin developing a truly probabilistic seismic design method for nuclear subsystems as opposed to the current deterministic methods. It is desirable to know the relative reliability effect due to the possible different

design procedures which are in use today. Both the criteria for evaluation and the design methods would need to be addressed. The important benefit for such work would be a better utilization of engineering resources to impose high reliability requirements where the system will benefit from a significant seismic risk reduction.

3.3.7 Further Develop Stochastic Interpretation of Response Spectrum

Reference 5 summarizes some recent theoretical work which has been performed to make use of random vibration theory to generate floor response spectra directly from ground response spectra without use of time history type analysis. Since there are many time histories which will match a given ground response spectrum, this new theory offers a design method which overcomes one of the sources of uncertainty in the presently used methods of subsystem response. It would be desirable to further test this theory since the method may prove to be both more accurate and more economical than present methods. It remains to provide convincing proof that these newer methods are indeed more accurate and that they can be integrated into present methods of design analysis.

3.4 Method for Non-Linear Evaluation

The method recommended to quantitatively deal with subsystem response nonlinearity is through the use of a variable K distribution with the allowable seismic excitation level on each type subsystem. Most design work in nuclear subsystems has been developed around two deterministic levels of seismic excitation, the OBE and SSE levels. Since much information has been developed around those ideas, the OBE and SSE levels make convenient evaluation points for the effects of non-linearity. In fact one form of nonlinearity has already been accounted for in this way and that is the values of damping. USNRC Regulatory Guide 1.61 as well as Table N-1230-1 of the ASME III Code recommend that different damping values be used in the design calculations depending on whether the seismic excitation is at the OBE or SSE level. While this treatment

does not accurately evalute the complex subject of damping and there are many theoretical difficulties which are not addressed, it does represent a first approximate accounting of the known effects which almost universally show damping increasing as seismic excitation increases.

It is a natural extension of this concept to refer all significant forms of nonlinearity besides damping to the same excitation levels and hence measure nonlinear effects by its overall increase on uncertainty of predicted response. It is believed that this technique will permit a proper preliminary accounting of the nonlinear subsystem response effect for Phase 1 of SSMRP.

4.0 SUBSYSTEM CLASSIFICATIONS

4.1 SSMRP Phase 1 Classification

For the Phase 1 SSMRP effort it is desirable to establish an overall computation scheme so that the relative importance of various uncertainties can be better understood. For the subsystems it is first necessary to establish which components are capable of influencing the overall seismic risk. Regulatory Guide 1.29 establishes a criteria for determining the components and equipment which are essential to reactor safety.

Contained in Table 4.1 is a list of safety-related components of light water reactor power plants. This list is intended to be as complete as practical. The various components are identified generically, i.e., similar components such as a particular valve design or actuator design are identified by component type rather than by system name or function.

The list includes only those components which have a safety-related function and should be seismically qualified in accordance with USNRC Regulatory Guide 1.29.

It should be noted, however, that there are many non-safety-related components that are not normally seismically qualified whose failure would be an initiating event for the use of safety-related equipment. Such components are not included herein.

4.1.1 Quantities

Estimates of the quantities of components for a typical power plant have been made. These estimates have been made on an order of magnitude basis only. The components are divided into four (4) quantity groups.

A - 1 to 5 items
B - 5 to 50 items
C - 50 to 100 items
D - 500 to 5000 items

Considerable effort is required to more accurately define component quantities. In fact, a large additional effort would be required to assign components to these groupings with a high degree of confidence.

It should be noted that there will be few gross variations in quantities between BWR and PWR plants; therefore, no such distinction has been made. In many cases other factors such as plant size, age (i.e., solid state vs. mechanical components) or A-E (i.e., valve type) can cause quantity variations.

4.1.2 Triad Classification Scheme

Table 4.1 contains approximately 140 different subsystems or components which may have distinctly different seismic characteristics. In order to reduce this number to a more manageable quantity for the Phase 1 SSMRP effort of 15 to 20 sets, a triad classification scheme was used. The triad categories and identification numbers are shown in Tables 4.1.2a, 4.1.2b, and 4.1.2c. Table 4.1 shows a typical classification of each component according to the triad identification numbers of Tables 4.1.2a, b, and c. It should be emphasized that this particular assignment of a triad to each component is not unique and in general specific plant information may differ with that used in Table 4.1. The purpose of Table 4.1 is to test the triad classification scheme and to identify the more commonly used triads for quantification of random and modeling uncertainty. The last column of Table 4.1 indicates a set number. The set number is the result of a tabulation in which the more commonly occurring triads are given a set number 1, 2, 3, etc.,

where each set number from 1 to 18 has a unique triad classification. The lowest set number 1 has the most components (24) with identical triad classifications, and sets 13 through 18 had only 2 components per set. Set 19 is a miscellaneous group of 24 items which each have different triad classifications. No further attention will be devoted to Set 19 in this report since an actual plant inventory and classification is likely to produce fewer triad sets than 18 which are distinctly different, and the identification of set 19 only illustrates some possible rare seismic qualification methods. A summary of the classification results is shown in Appendix D where each of the sets is identified, and a box is drawn around typical types of components which are considered representative of the group.

TABLE 4.1

INVENTORY

	Quantity Group	Expected Dynamic Behavior Identification Number From Table 4.1.2a	Method of Seismic Qualification, Identification Number From Table 4.1.2b	Response Parameter Used, Identification Number from Table 4.1.2c	Set Number
Structures					
Parting Walls	B	1.1	2.3	3.4	6
Floors and Ceilings	B	1.1	2.3	3.4	6
Door Assemblies	B	1.5	2.6	3.5	19
Windows	B	1.1	2.1	3.4	7
Intake Structure	A	1.2	2.1	3.4	1
Ice Condensor Suppression Structure	A	1.2	2.1	3.4	1
Active Mechanical Equipment					
(except valves)					
Large Horizontal Centrifugal Pumps	B	1.2	2.5	3.1	3
Small Horizontal Centrifugal Pumps	B	1.2	2.6	3.1	8
Vertical Centrifugal Pumps	A	1.2	2.5	3.1	3
Reactor Coolant Pump (PWR) fly wheel	A	1.3	2.3	3.4	9
Reactor Coolant Pump (PWR) seals and Pressure boundary	A	1.2	2.3	3.4	4
Reactor Coolant Pump Rotor	A	1.2	2.3	3.4	4
Recirculation Pump (BWR) pressure boundary	A	1.2	2.3	3.4	4
Diesel Generator Unit (includes diesel engine, generator and numerous small pumps, controls, cooling, etc.	A	1.9	2.6	3.1	13
Air compressors (not all plants)					

INVENTORY (Table 4.1 cont'd)

	Quantity Group	Expected Dynamic Behavior, Identification Number From Table 4.1.2a	Method of Seismic Qualification, Idenfification, Number From Table 4.1.2b	Response Parameter Used, Identification Number from Table 4.1.2c	Set Number
Active Mechanical Equipment (cont'd)					
Large motors > 50 HP	B	1.2	2.1	3.5	14
Small motors ≤ 50 HP	C	1.2	2.1	3.5	14
Fractional HP motors	B	1.2	2.5	3.1	3
Limitorque motors	C	1.2	2.5	3.1	3
Cooling fans mounted to structures	B	1.2	2.5	3.1	3
Fan Coil Units (includes fans and coils)	B	1.2	2.5	3.1	3
Cooling fans internal to ducts	B	1.2	2.5	3.1	3
Air Conditioners	A	1.7	2.5	3.1	19
Air Coolers	B	1.2	2.1	3.4	1
Cranes	A	1.4	2.3	3.4	10
Hoists	A	1.4	2.3	3.4	10
Water Chillers	B	1.2	2.1	3.4	1
Shafts	B	1.1	2.1	3.4	7
Couplings	B	1.1	2.1	3.4	7
Valves and Related Equipment					
Stemmed Valves (gate, globe, angle butterfly, etc)	C	1.5	2.6	3.1	2
Relief Valves (several types)	B	1.5	2.6	3.1	2
Swing Check Valves	C	1.5	2.6	3.1	2
Ball Check Valves	C	1.4	2.6	3.1	5

INVENTORY (Table 4.1 cont'd)

Valves and Related Equipment (cont'd)

Duo Check Valves (flapper)
Piston Actuators
Air Diaphragm (spring loaded) actuators
Hydraulic Actuators (rare)
H & V Dampers
Solenoid Valves
Valve Dampers
Pressure Regulating Valves
H & V Louvers

Passive Mechanical Components

Heat Exchangers (include steam generators including -

tubes
tube sheets
shells
water boxes
tube supports
case and attachments

Quantity Group	Expected Dynamic Behavior Identification Number From Table 4.1.2a	Method of Seismic Qualification, Identification Number From Table 4.1.2b	Response Parameter Used, Identification Number from Table 4.1.2c	Set Number
B	1.5	2.6	3.1	2
A	1.5	2.5	3.2	12
C	1.5	2.5	3.2	12
A	1.5	2.5	3.5	19
B	1.4	2.5	3.2	19
C	1.4	2.5	3.1	19
A	1.5	2.5	3.1	19
C	1.5	2.6	3.1	2
B	1.4	2.3	3.4	10
B	1.7	2.6	3.1	19
	1.1	2.1	3.4	7
	1.2	2.1	3.4	1
	1.2	2.1	3.4	1
	1.2	2.1	3.4	1
	1.1	2.3	3.4	6
	1.2	2.1	3.4	1

INVENTORY (Table 4.1 cont'd)

Passive Mechanical Components (cont'd)

	Quantity Group	Expected Dynamic Behavior Identification Number From Table 4.1.2a	Method of Seismic Qualification, Identification Number From Table 4.1.2b	Response Parameter Used, Identification Number from Table 4.1.2c	Set Number
Large Tanks, i.e., refueling water, condensate storing	A	1.4	2.4	3.4	15
Small Tanks	B	1.4	2.4	3.4	15
Pressurized Tanks and Vessels	B	1.2	2.1	3.4	1
Accumulators	B	1.2	2.1	3.4	1
Line Surge Tanks	B	1.2	2.1	3.4	1
Strainers (general integrity not function required)	B	1.1	2.3	3.4	6
Filters (liquid)	B	1.5	2.5	3.2	12
H & V Filters including HEPA	B	1.2	2.1	3.4	1
HEPA and other Filter Cases	B	1.2	2.1	3.4	1
Electrical Penetrations	B	1.3	2.6	3.1	11
Piping Penetrations	B	1.3	2.3	3.4	9
Equipment Supports	C				
pads		1.3	2.3	3.4	9
large beams		1.1	2.1	3.4	7
plates		1.2	2.1	3.4	1
tubing		1.2	2.3	3.4	4
unistrut		1.1	2.1	3.4	7
Large welded piping segments (pressurized) or fittings > 6"	D	1.2	2.1	3.4	1

INVENTORY (Table 4.1 cont'd)

Passive Mechanical Components (cont'd)

	Quantity Group	Expected Dynamic Behavior, Identification Number From Table 4.1.2a	Method of Seismic Qualification, Identification Number From Table 4.1.2b	Response Parameter Used, Identification Number from Table 4.1.2c	Set Number
Small welded piping segments (pressurized) or fittings ≤ 6"	D	1.2	2.1	3.4	1
Unpressurized piping and fittings (all sizes)					
Small Tubing (generally air lines, and instrument sensing) - 3/4" usually uses compression fittings)	C	1.2	2.1	3.4	1
Large Tubing - 3/4" generally instrument sensing	D	1.2	2.3	3.4	4
Pipe and tubing guides					
Pipe and tubing supports	C	1.2	2.3	3.4	4
Pipe Restraints	D	1.3	2.3	3.4	9
Pipe Rupture Restraints - plastic:	D	1.3	2.3	3.4	9
"U" bolts	C	1.2	2.3	3.4	4
honeycomb pads	B				
		1.9	2.4	3.9	19
		1.9	2.4	3.5	19
Platforms	B	1.2	2.1	3.4	1
Crane Rails	B	1.1	2.3	3.4	6
H & V Ducts	B	1.2	2.1	3.4	1
Spent Fuel Pool Storage Racks	A	1.5	2.1	3.4	19
Pipe Snubbers - Mechanical	C	1.4	2.8	3.9	16
Pipe Snubbers - Hydraulic	C	1.4	2.8	3.9	16
Pipe Hangers	C	1.1	2.3	3.4	6

INVENTORY (Table 4.1 cont'd)

Passive Mechanical Components (cont'd)

Flanged Connections
Instrument Tubing Connections

Electrical Equipment
Transformers (4kV and 480V)
Large Switches
Power Cables
Panels
Switchgear
Batteries Cells
Battery Cell Rack
Battery Chargers
Rigid Conduit
Cable Trays
Connectors
Junction and Terminal Boxes
Pull Boxes
Motor Generators
Motor Control Centers
Cabinets
Lighting
Fuses

Quantity Group	Expected Dynamic Behavior Identification Number From Table 4.1.2a	Method of Seismic Qualification Identification Number From Table 4.1.2b	Response Parameter Used, Identification Number from Table 4.1.2c	Set Number
B	1.8	2.3	3.4	19
D	1.8	2.6	3.1	17
B	1.2	2.1	3.4	1
C	1.4	2.6	3.1	5
C	1.4	2.3	3.4	10
B	1.5	2.6	3.1	2
B	1.5	2.6	3.1	2
C	1.9	2.6	3.2	19
B	1.1	2.3	3.4	6
B	1.9	2.6	3.1	13
D	1.2	2.9	-	19
D	1.2	2.1	3.4	1
D	1.3	2.6	3.1	11
B	1.2	2.6	3.1	8
C	1.2	2.5	3.1	3
A	1.2	2.5	3.1	3
B	1.5	2.6	3.1	2
B	1.2	2.6	3.1	8
C	1.2	2.6	3.1	8
C	1.3	2.6	3.1	11

INVENTORY (Table 4.1 cont'd)

Electrical Equipment (cont'd)

	Quantity Group	Expected Dynamic Behavior Identification Number From Table 4.1.2a	Method of Seismic Qualification, Identification Number From Table 4.1.2b	Response Parameter Used, Identification Number from Table 4.1.2c	Set Number
Circuit Breakers	C	1.8	2.6	3.1	17
Switches, solid state	C	1.3	2.5	3.1	19
Insulators	C	1.3	2.3	3.3	19
Flexible conduit	C	1.5	2.9	-	19
Cable tie down straps	D	1.4	2.9	-	19
Pushbutton Switches	C	1.4	2.6	3.1	5
I & C Switches	C	1.4	2.6	3.1	5
I & C Cable	D	1.4	2.3	3.4	10
Cable Strain Relievers	D	1.5	2.6	3.1	2
Instrumentation					
Sensors:					
transducers	C	1.2	2.5	3.1	3
thermocouples	B	1.1	2.6	3.1	19
level probes	B	1.4	2.6	3.1	5
position switches	C	1.4	2.6	3.1	5
Sensing Lines	C	1.2	2.3	3.4	4
Signal Conditioner	C	1.9	2.7	3.6	18
Transmitters	C	1.9	2.7	3.6	18
Connectors (co-axial, single element, multiple element)	D	1.3	2.6	3.1	11
Indicating Gauges	B	1.4	2.6	3.1	5

INVENTORY (Table 4.1 cont'd)

Instrumentation (cont'd)

Annunciator
Indicating Lights
Controllers
Electrical Power Monitors
Neutron Flux Monitors
Electro-mechanical relays
Solid State Relays
Solid State Logic Boards
Radiation Monitors

Reactor Components (Assembly)
Fuel Channels
Fuel Assemblies
Control Rods
Core Barrel
Core Supports (gussets, etc.)
Spacers
Core Support Plates
Control Rod Guides
Control Rod Drives
Jet Pumps - BWR only
Sparagers

Σ = 140 types of components

Quantity Group	Expected Dynamic Behavior, Identification Number From Table 4.1.2a	Method of Seismic Qualification, Identification Number From Table 4.1.2b	Response Parameter Used, Identification Number from Table 4.1.2c	Set Number
P	1.4	2.6	3.1	5
B	1.2	2.6	3.1	8
B	1.5	2.6	3.1	2
B	1.5	2.6	3.1	2
B	1.4	2.6	3.1	5
C	1.5	2.6	3.1	2
C	1.3	2.6	3.1	11
B	1.2	2.6	3.1	8
C	1.2	2.6	3.1	8
A	1.5	2.2	3.4	19
C	1.1	2.8	3.5	19
C	1.5	2.8	3.4	19
C	1.2	2.8	3.4	19
A	1.2	2.1	3.4	1
B	1.3	2.3	3.4	9
B	1.3	2.3	3.4	9
A	1.2	2.6	3.4	19
B	1.1	2.1	3.4	7
B	1.5	2.8	3.9	19
B	1.2	2.1	3.4	1
A	1.2	2.1	3.4	1

TABLE 4.1.2a

1.0 EXPECTED DYNAMIC BEHAVIOR (UP TO SSE LEVEL)

1.1 Nearly Linear - Simple Flexible Structure

1.2 Nearly Linear - Complex Flexible Structure

1.3 Nearly Linear and Rigid

1.4 Significant Geometric Nonlinearity - Simple Flexible Structure

1.5 Significant Geometric Nonlinearity - Complex Flexible Structure

1.6 Significant Material Nonlinearity - Simple Flexible Structure

1.7 Significant Material Nonlinearity - Complex Flexible Structure

1.8 Significant Nonlinearity and Rigid

1.9 Significant Compound Types of Nonlinearity - Flexible

TABLE 4.1.2b

2.0 METHOD OF SEISMIC QUALIFICATION

2.1 Linear Dynamic Analysis with Required Response Spectrum

2.2 Linear Dynamic Time History Analysis

2.3 Equivalent Static Analysis with Required Response Spectrum

2.4 Nonlinear Dynamic Time History Analysis

2.5 Shake Table Biaxial Testing with Narrow Band Required Response Spectrum

2.6 Shake Table Biaxial Testing with Broad Band Required Response Spectrum

2.7 Shake Table Biaxial Testing with Required Power Spectral Density and Duration

2.8 Combination In-Situ Testing and Dynamic Analysis with Required Response Spectrum

2.9 No Formal Procedure Known

TABLE 4.1.2c

3.0 RESPONSE PARAMETER USED (UP TO FAILURE)

3.1 Max Input Acceleration (Response is Binary Operability)

3.2 Max Input Velocity (Response is Binary Operability)

3.3 Max Response Peak Stress (Brittle Behavior)

3.4 Max Primary Stress and Fatigue Analysis (Ductile Behavior)

3.5 Max Response Critical Deformation

3.6 Fatigue Damage Test (Response is Binary Operability at an Equivalent Cycle Value of Input Stress Reversals, i.e., PSD + Time)

3.7 Critical Size Crack Growth of Flawed Structure

3.8 Critical Total Ratchet Strain Response

3.9 Multi-State Severity Parameter (Combination)

4.2 Subsystem Relationship to Systems

The subsystems identified in Section 4.1 are part of safety systems in the nuclear plant. Regulatory Guide 1.29 identifies the following system type functions of concern:

- Reactor Coolant Pressure Boundary
- Reactor Core & Vessel Internals
- Systems For:
  - Emergency Core Cooling
  - Post Accident Containment Heat Removal
  - Post Accident Containment Atmospheric Cleanup
  - Shutdown
  - Residual Heat Removal
  - Spent Fuel Storage
- BWR Steam Line to Turbine Stop Valve
- PWR Steam and Feed Lines from Secondary of S.G. to Containment Isolation
- Cooling Water
- Cooling Water & Seal Water Systems for Equipment Like Pumps
- Fuel Systems for Emergency Equipment
- Electric and Mechanical Devices and Circuits-Isolation Protection System
- Systems for Monitor Functions
- Spent Fuel Storage Pool & Racks
- Reactivity Control Systems - Drives and Boron Injection
- Control Room
- Primary and Secondary Reactor Containment
- Systems with Radioactive Materials (Not Waste Management)
- IE Electric Systems - Onsite Power

The detail plant specific inventory should identify which safety system the components are in and establish a relationship between the numbers of subsystems which are contained within each plant safety system. Due to the very large number of subsystems which are implied by Table 4.1, i.e., 10s of thousands in a nuclear plant, and the fact that all of

these subsystems will experience simultaneous dynamic excitation in case of a seismic event, it is important to account for all potential failures which may occur.

4.3 Alternative Subsystem Response Classification

The Triad Classification Scheme described in Section 4.1 was chosen from an original list as shown in Table 4.3. The reasons for selecting this triad combination are outlined as follows.

The objective was to reduce the large inventory list in Table 4.1 from 140 groups down to no more than 15 or 20 groups for the Phase 1 part of SSMRP. The three chosen characteristics 1) expected dynamic behavior, 2) method of seismic qualification, and 3) response parameter used, appeared to provide the greatest likelihood of achieving that goal because they had a strong influence on the dynamic behavior. Of the schemes rejected such as 1) component function, 2) systems function, and 3) industry standard used, the first two have almost no relationship to the dynamic behavior while the third one does not pin down in enough detail which of the acceptable alternative methods was used.

TABLE 4.3

SUBSYSTEM CLASSIFICATION METHODS CONSIDERED

COMPONENT FUNCTION

EXAMPLES: PUMPS, VALVES, PIPING, ELECTRICAL PANELS, REACTOR COMPONENTS

EXPECTED DYNAMIC BEHAVIOR

EXAMPLES: LINEAR, NONLINEAR, RIGID, FLEXIBLE, SIMPLE, COMPLEX

SYSTEMS FUNCTION

EXAMPLES: REACTOR COOLANT, EMERGENCY CORE COOLING, CONTAINMENT SPRAY

METHOD OF SEISMIC QUALIFICATION

EXAMPLES: RESPONSE SPECTRUM ANALYSIS, TIME HISTORY ANALYSES, TESTING OR COMBINATION ANALYSIS AND TEST

INDUSTRY STANDARD USED

EXAMPLES: ASME CODE, IEEE 344

RESPONSE PARAMETER USED

EXAMPLES: MAX INPUT ACCELERATION, MAX INPUT VELOCITY, MAX RESPONSE PRIMARY STRESS

COMBINATIONS OF ABOVE

5.0 METHODS OF SEISMIC RESPONSE EVALUATION

5.1 Standards for Qualification

There are three general methods of seismic qualification for subsystems a) analysis, b) test, and c) combinations of analysis and test. The industry standard most used for analysis is the ASME Section III Boiler and Pressure Vessel Code which provides analysis requirements for such components as:

- Pressure Vessels
- Pumps
- Valves
- Piping
- Metal Containment
- Component Supports
- Core Support Structures
- Concrete Vessels and Containment

The ASME Section III Code (Reference 6) emphasizes the role of primary type stress (stresses related to static or dynamic equilibrium) as a qualification parameter. Since the ASME III Code was developed originally for static type loadings such as pressure and weight, the increasing attention to seismic and other dynamic loading has been treated in a somewhat ad hoc fashion. The ASME III code has published two non-mandatory appendices, Appendix F, Rules for Evaluation of Level D Service Limits, and Appendix N, Dynamic Analysis Methods, which adapt the static design methods of the code to dynamic situations which occur with seismic type loading.

The ASME III Code also has requirements for secondary stress and fatigue effects which supplement the primary stress requirements. Normally, however, these effects are not critical conditions for design as a result of seismic loading.

The ASME III Code recognizes the role of testing in connection with component qualification through Mandatory Appendix II, Experimental Stress Analysis, but this appendix is related to static or quasi-static methods of testing as opposed to dynamic seismic testing covered by IEEE 344 (Reference 7) for electrical equipment. The ASME III Code therefore, covers the seismic qualificaton design aspects which are amenable to primary stress analysis but does not cover the design problems related to operability which are of concern for active type components such as pumps and valves.

It has been the design practice for several years to use a dynamic test procedure to qualify Category I seismic equipment which is either active (must perform some functional movement to correctly operate) or is too structurally complex to be amenable to accurate primary stress analysis such as most electrical or electronic equipment. In these cases, the ability of a mechanical or electrical device to correctly operate during or after a seismic event is qualified by a shaker table type test.

The IEEE-344-1975 (Reference 7) is the current industry standard which outlines recommended procedures for such testing. In IEEE-344, two important quantities are defined, the required response spectrum (RRS) and test response spectrum (TRS). The RRS is the specified seismic excitation for which it is desirable to qualify the equipment. The TRS is the actual test excitation used and it is required that the TRS essentially envelope the RRS at all frequencies of interest. This introduces a variable degree of conservatism for each piece of equipment, however, test reports are required to report both curves so that it is not necessary to treat this source of conservatism as being uncertain in SSMRP if the test reports are available.

On the other hand, if only a sampling of test reports is available for a plant seismic risk analysis, it will be necessary to describe this difference between TRS and RRS in a probabilistic (uncertain) manner.

There are many alternative methods of seismic simulation outlined by IEEE-344 such as continuous sine, sine beat, decaying sine, sine sweep, multi-frequency, random motion, or combinations which can be used. The general idea is to simulate conservatively the destructive nature of the expected seismic input motion, but it is clear that not all alternative methods will produce a consistent level of severity on the equipment tested and that a good degree of judgment must be exercised both by the writer of the equipment specifications and the testing laboratory. In addition, earthquake effects cause three simultaneous translation motions to occur in general and in some cases significant rotational motions at the support points of equipment. Current methods are limited to testing two simultaneous translation motions as input to equipment testing, therefore, this introduces a level of uncertainty in the qualification procedure in addition to the basic uncertainties associated with characterizing seismic motion by a response spectrum.

There is one major difference between the two generally used methods of seismic qualification (analysis and test), and that involves the parameter used to monitor the response. In the case of analysis, the maximum stress, strain, load, or deformation (structural mechanics quantities) are the focal point for acceptability while in a test, the operability or failure to operate (a binary systems state often called fragility) is the focal point for acceptability. The stress, strain, load, or deflection, of the analysis method provides an analytical link to component fragility through other structural mechanics disciplines such as fracture mechanics or buckling analysis. The two methods of seismic qualification are not readily interchangeable because each measures a different response quantity and therefore the use of one or the other depends on both judgment of which method is most appropriate, as well as the economics of qualification.

There are numerous other complex effects reported in References 1 & 6 which make the result of seismic test qualification more uncertain than might

be readily apparent from the idea that the equipment has experienced simulated seismic testing.

Recognition of this fact has given rise to a mode of seismic qualification wherein one attempts to combine the desirable features of testing with the desirable features of analysis. Where a significant degree of these two methods has been used, the equipment is said to be qualified by a combination of analysis and test.

The varieties of such combination procedures are many. As an example, by measuring frequencies, modes, stiffness or damping, a dynamic analysis of a complex structure can be greatly improved by adjusting the modeling parameters which would otherwise be determined purely from analysis. As another example, the critical clearances of a control rod drive mechanism may be studied as to their effect on SCRAM time by test, where a dynamic analysis can be used to quantify the simultaneous input seismic effects on the critical clearances.

In general the two methods (analysis and test) are complementary and there is a compelling technical reason to use both if the objective is to gain as much information as possible concerning seismic dynamic response with a fixed resource allocation. However, except in a limited number of cases of special interest such as the control rod drive mechanism previously mentioned, either testing or analysis alone will be used if the degree of general conservatism which this requires can be economically tolerated.

There are other supplemental standards which play a role in seismic qualification used in nuclear components contained in USNRC Regulatory Guides 1.48, 1.60, 1.61, 1.92, and the USRNRC Standard Review Plan. These guides and/or standards generally introduce a level of conservatism to the process of seismic qualification which must be evaluated as part of the SSMRP project. The only way that the overall effects of such

standards on seismc risk can be measured is through quantifying both the nominal margins and the levels of uncertainty which result from applying all the standards as a constraint to the design process. The method of quantifying both of these effects for subsystem response is addressed in Section 5.7 of this report.

5.2 Differences Between Testing and Analysis

As discussed in Section 5.1, the seismic qualification by analysis or by test involves different parameters to monitor the response. The structural mechanics response quantities stress, strain load cr deformation, can be conveniently calculated through computerized analysis due to all of the significant seismic translations or rotations in three dimensions which are of interest. The only limitation is the expense required for the computer analysis. The result of such seismic response analyses are either maximum stress or load quantities if the response spectrum analysis method is used, or time histories of stress or load when time history analysis is used.

In contrast with these mechanics response parameters, the main response characteristic of interest in an operability test is the binary state of whether the component operates or not. A comparison of these two qualification methods is shown in two flow diagrams of Figure 5.2a and b. Here we see that both procedures ultimately qualify the same Binary Fragility State, but in Figure 5.2a, there are fewer steps. The major conservatism and uncertainty in Figure 5.2a is introduced at the inputs to the shaker table test. In Figure 5.2b the additional steps to relate the ASME Code criteria to fragility state involves Stress Analysis plus Failure Analysis. Therefore, major sources for uncertainty and conservatism in Figure 5.2b is through the Safety Margin which relates code criteria to fragility state.

Because no mechanics response parameters are of direct use or interest in Figure 5.2a, it is necessary to quantify the fragility state by use

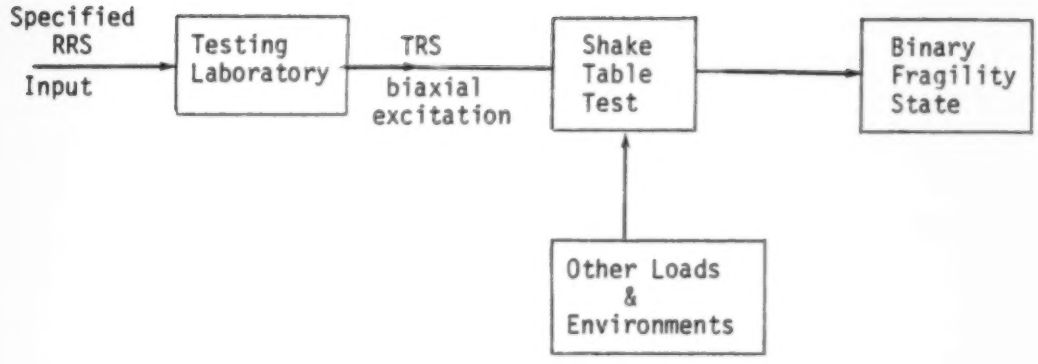

FIGURE 5.2a

SUBSYSTEM SEISMIC QUALIFICATION BY TEST

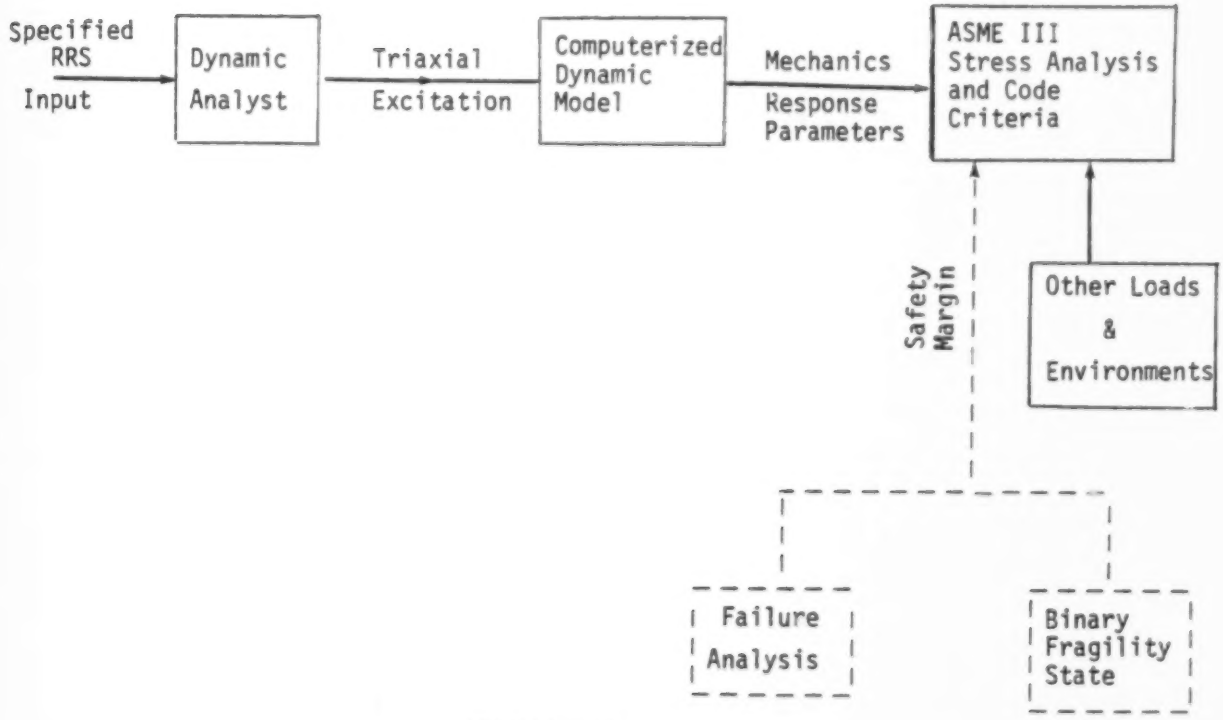

FIGURE 5.2b

SUBSYSTEM SEISMIC QUALIFICATION BY ANALYSIS

of the Input RRS as the independent parameter. That is, at some scaled up value of the RRS, failure will occur. In Figure 5.2b similarly, at some scaled up level of the Mechanics Response Parameters, failure will occur. These concepts have important implications in developing the uncertainty quantification in Section 5.7 of this report.

It may be desirable to better relate the concepts of Figures 5.2a and 5.2 b by development of a multiple-quantity severity parameter as discussed in Section 3.3, where the influence of all significant modes of failure were integrated for all environmental effects including seismic excitation.

Such an approach as a minimum should consider the combined effects of a) primary stress overload and b) cumulative fatigue damage due to stress reversals. A suggested format for such severity parameter is as follows:

$$\left(\frac{\sigma_m}{\sigma_{mf}}\right)^{n_1} + \left(\frac{U}{U_f}\right)^{n_2} + \left(\frac{E_r}{E_{rf}}\right)^{n_3} \leq 1.0 \qquad (1)$$

where

σ_m is the maximum primary stress due to all loading
σ_{mf} is the failure primary stress
U is the fatigue usage due to all stress reversals
U_f is the failure fatigue usage
E_r is the maximum cumulative ratchet strain
E_{rf} is the failure ratchet strain
n_1, n_2, n_3 are experimentally determined contants

The general form of equation (1) has been successfully used for similar related complex failure phenomena such as high cycle fatigue and high temperature metals design, Reference 6. In order to make use of a combined severity factor to better relate testing to analysis, it would

be helpful to associate a seismic test response parameter with one or more usual structural mechanics quantities, such as stress, strain or acceleration. This can be done by requiring that the analytical response at one or more cardinal points where failure is expected be closely matched with the measurement. A cardinal point, for example, can be a point through which dynamic loadings are transmitted to the component in question as opposed to an appurtenance which responds in a manner nearly independent of the global dynamic characteristics of the component. Normally during seismic testing some of this type data is recorded, but it is not presently used in a direct way for seismic qualification. If this supplementary measurement were sensitive to all three potential translations, then it may be possible to better account for complex seismic input effects such as simultaneous 3-dimensional translations and possibly even rotational inputs.

Such measurements together with the development and use of a parameter like the left hand side of equation (1) would go a long way toward unifying the divergent concepts presently in place for seismic qualification by test and by analysis.

5.3 Multiple Input Response Cases

When the subsystem is supported at more than one point such as piping, special problems are encountered which introduce uncertainty into the seismic qualification. For example, the seismic input motions are often different at the different support points. If a computerized analysis is capable of dealing with the multiple input situation in a rigorous way (e.g., considering independent support motions), the resulting critical response stresses may be considerably lower than if an envelope of the floor support response spectra were used as a single input. As an example, a piping system supported in several regions with differing spectra is now treated by applying a single spectra representing the envelope of all spectra involved. This penalizes segments of the piping in low seismic excitation areas, no matter how remote they are from high

seismic areas. Methods have been derived and implemented in computer programs (NUPIPE, KWUROHR, SUPERPIPE) which eliminate the need for spectral enveloping; it is permissible to assign unique spectra to groups of supports. The method makes use of influence coefficient matrices which provide a measure of the capability of each support to cause displacements at all other locations in the system. The relative support motion effects are calculated in a similar manner.

An example problem published in Reference 18 showed the enveloping procedure results to be, on the average, 50% higher than the multiple independent spectra results. However, depending on the configurations and relative disparity of the spectra at different supports, it is possible to get higher results with the independent support motion procedures, since the application of the influence matrices in the solution prevents the contribution of anti-symmetric modes from disappearing, as they normally would in the uniform support motion approach.

5.4 Large Equipment Seismic Qualification

Some equipment such as large isolation valves, reactor internal assemblies, or large diesel generators are not readily testable on shaker tables even though from the standpoint of complexity and nonlinearity they are not well suited for pure analysis type seismic qualification. In these cases the method of qualification must necessarily involve both analysis and testing. Often substructuring by analysis is used to combine subcomponent tests with analysis of overall assemblies. This is not an entirely satisfactory procedure from the standpoint of introducing uncertainty into the qualification process. There is no way short of in-situ type testing which can properly reflect the complex dynamic behavior which results in some cases.

An ideal source for improving the state of seismic dynamic information for the critical reactor internals is through the flow vibration testing which is normally part of licensing the reactor. Through this program,

vibration sensors measure the response to flow induced vibration which in turn provides valuable information to refine modes and frequencies of the seismic dynamic analysis. Other tests involving small arrays (4 to 16) of fuel bundles plus scale model testing of larger arrays are used to help improve the accuracy of complex dynamic models. Usually, however, such information is considered proprietary by reactor manufacturers. The degree of response uncertainty of such equipment can be quite variable depending on the methods used and the availability of key test information.

5.5 Nonlinear Dynamic Response

Nonlinear dynamic analysis has been performed on a limited number of reactor components. Examples include PWR reactor assemblies and spent fuel storage racks. On PWR assemblies, the presence of several thermal expansion gaps causes a geometric type nonlinearity which is usually treated in the dynamic analysis (Reference 9). Spent fuel storage racks involves gaps between the fuel assemblies and the rack structure which is oten modeled as a nonlinearity. Also the mounting of some fuel racks permits sliding and potential overturning which require nonlinear analysis.

There are several problems with use of nonlinear analysis that tends to minimize its use except where necessary. The first is its much higher cost compared with linear analysis. Another problem is that results from nonlinear analysis cannot be accurately scaled to other load input values and one faces the problem of how to add stress results from different individual loadings which combine. While these problems are real in the sense that they only apparently disappear when linear analysis is used, they do cause uncertainty to be present if they are not analyzed in a realistic nonlinear fashion.

One area where elementary type material nonlinearity has been dealt with involves pipe whip type analysis, but this is normally not done for piping seismic analysis. It has been often stated (Reference 10) that

nonlinear material behavior is a source of considerable conservatism in linear seismic dynamic analysis, and therefore a realistic evaluation of its effect will be essential to gaining insight into seismic margin. Simplified elastic-plastic analysis is usually all that can be performed without causing analysis costs to become exhorbitantly high. The simplified analysis can be one dimensional and use of a simple yield surface with a piece-wise linear moment-curvature relationship can be used to reduce piping problems to a feasible analysis. This procedure is currently used for the pipe whip analysis under LOCA blowdown forces.

Another possible technique for preliminary analysis that can be used in Phase 1 of SSMRP is the inelastic response spectra method proposed by Newmark and Hall (Reference 11). Perhaps further development and extension of this method would better qualify its use for nuclear reactor analysis.

5.6 Sources of Response Uncertainty (Random and Modeling)

Beginning from the assumption that seismic response qualification is performed by a) analysis, b) test, or c) combinations of analysis and test, there are a large number of distinctly different sources of uncertainty which may cause actual seismic response to be different from the predicted response which is developed in the qualification. In order to better identify these sources, the following Table 5.6.1 has been developed so that generic groups of uncertainty can be discussed. The intent of Table 5.6.1 is to exhaustively identify all sources of subsystem response uncertainty of interest to the SSMRP program. The test of whether Table 5.6.1 accomplishes that intent depends on how easily each specific source of uncertainty which comes to mind can be placed in a category. Each category will be discussed to illustrate how the specifics fit into the generic groups.

5.6.1 Mass, Stiffness, and Damping

The equations of motion which are commonly used to describe dynamic behavior involves three parameters, mass, damping, and stiffness

TABLE 5.6.1

SUBSYSTEM RESPONSE UNCERTAINTY GENERIC GROUPS

1. Mass
   - Magnitude
   - Distribution
2. Stiffness
   - Magnitude
   - Distribution
3. Damping
   - Magnitude
   - Distribution
4. Discretization
5. Prediction Theory
   - Beam
   - Shell
   - 3-D
   - Testing
6. Nonlinearity
   - Geometric
   - Material Plasticity
   - Compound
7. Decoupling & Boundary Conditions
8. Design Errors
9. Time Dependent Changes
   - Flow Growth
   - Fatigue
   - Stress Corrosion
   - Aging
   - Wear Out

which are associated with the subsystem itself. The mass magnitude is probably the most accurate parameter to evaluate and under most circumstances would be known better than the other two parameters. The mass uncertainty would normally be associated with tolerances of the fabricated or manufactured subsystem as well as uncertainty of the densities of materials involved. Analysis of the part drawings as well as quality control procedures will normally be a good source for identifying uncertainty of mass magnitude. A generic uncertainty description of ±5% of the nominal mass values at the 10%, 90% probability values is an NSC assignment if no more specific source of information is available.

There are some circumstances where mass magnitude may have a more significant uncertainty effect and that involves cases where fluid structure interaction is significant. For such cases a ±50% mass uncertainty effect would not be uncommon. Examples of such effects occur when the dynamic motions of structural elements forces fluids to experience high local or general accelerations as described in References 12, 13, and 14. These are sometimes called hydrodynamic or virtual mass effects. Another class of problems where fluid structure interaction causes a significant mass uncertainty effect is in sloshing problems as discussed in Reference 15 where fluid surface wave effects are important. In most fluid structure interaction prediction problems, the fluid flow is treated as irrotational and sometimes as incompressible. In many cases these assumptions are sufficiently accurate to allow a reasonable accurate prediction, but unless care is taken to compare the theory used with experimental results, the fluid structure interaction can produce major uncertainties of seismic response prediction.

The stiffness prediction depends on some quantities that are also influenced by design and manufacturing tolerances. However, since stiffness usually depends on more complex geometrical and material relationships than mass, it is generally more uncertain. Stiffness

TABLE 5.6.1.1

NSC Generic Stiffness Uncertainty Assignments
at the 10%, 90% Probability Levels

For Simple Structures, ±15% of expected values

For Complex Structures, ±30% of expected values

The terms simple and complex have the same meaning as used in the Appendix A Questionnaire.

For complex geometries (such as bolted connections) or nonlinear construction (such as reactor internals where sliding may occur during seismic event) idealized as linear, +200%, -70% of expected values can be encountered.

also depends on material properties such as Young's modulus and to some extent Possions ratio. Careful analysis and testing is usually necessary to establish error free stiffness characteristics of subsystems and since seismic qualification is often performed by pure analysis, there will be considerable response uncertainty due to uncertainty of stiffness regardless of the theory used for prediction. Table 5.6.1.1 describes generic values for stiffness uncertainty which can be used if no more specific source of information is available.

Damping is the most difficult parameter to evaluate in a dynamic analysis because it is not obtainable from simple property or geometry relationships. Damping is usually treated as an equivalent energy dissipation for the subsystem represented by ideal linear dashpots. Since rarely is damping linear, almost all realistic values for damping must be measured for actual components or structures at specific excitation levels. Minor dimensional differences between actual components and those tested can cause the damping values to vary. Generally damping values are the most uncertain of the three dynamic characteristics of structures or subsystems.

In order to assign some realistic preliminary generic uncertainty distributions, some important facts should be considered. First, design damping values are normally assigned conservatively, which means that the uncertainty on damping would be biased relative to the design numbers usually used. Next, since damping is predominately nonlinear, it is helpful to specify damping uncertainty with reference to an amplitude level. The convenient reference used in the past to specify amplitude level dependency has been the OBE and SSE seismic excitation levels. There is some ambiguity with this approach since the ratio of seismic to all other static and dynamic loading will influence the effective damping present. However, under the assumption that an average condition of load

TABLE 5.6.2

NSC GENERIC DAMPING UNCERTAINTY ASSIGNMENTS
AT THE 10%, 90% PROBABILITY LEVELS

Structure or Component	Percent Damping					
	OBE			SSE		
	Reg. Guide 1.61	10% Prob. of Exc. (1)	90% Prob. of Exc. (2)	Reg. Guide 1.61	10% Prob. of Exc. (1)	90% Prob. of Exc. (2)
Equipment and large diameter piping systems >12 inches diameter	2	6.0	0.5	3	10.5	0.75
Small diameter piping systems ≤12 inches diameter	1	5.0	0.5	2	8.0	1.0
Welded steel structures	2	4.0	0.5	4	10.0	2.0
Bolted steel structures	4	8.0	1.0	7	17.5	3.5
Prestressed concrete structures	2	5.0	1.0	5	15.0	2.5
Reinforced concrete structures	4	10.0	2.0	7	21.0	3.5

NOTES: (1) The probability that the damping will exceed the values in this column is 10 percent.
(2) The probability that the damping will exceed the values in this column is 90 percent.

combination exists, the following generic values for damping uncertainty have been assigned in Table 5.6.2 by NSC at the 10%, 90% probability levels relative to the design values used in Regulatory Guide 1.61. These values are recommended in those cases where no more specific source of information is available. However, no specific probability distribution is suggested here.

5.6.2 Discretization and Prediction Theory

When analysis is used to perform seismic qualification, some discretization scheme must be used to render the dynamic analysis tractible. The most powerful method in common use today is the finite element method where the analyst breaks the actual structure into discrete degrees-of-freedom which are subsequently analyzed. This process of breaking the original structure into discrete parts for analysis always introduces some uncertainty in the seismic response prediction, and this effect must be accounted for in SSMRP.

Closely coupled to the discretization process in the prediction theory used where mathematical theories have been developed to allow various simplifications to the prediction process. All components and structures are three-dimensional in nature, yet they are commonly analyzed by use of simplified theories such as beam, plate, shell, etc. Use of these theories introduces uncertainty in seismic prediction and must be accounted for in the SSMRP program.

5.6.3 Nonlinearity

Other forms of dynamic nonlinearity besides damping are often present to a significant degree in safety-related equipment. For purposes of classification, three types have been considered a) geometric, b) material plasticity, and c) compound. Gaps plus the influence of large deformation theory give rise to typical geometric effects. Also some sloshing phenomena (Reference 16)

involving complex wave action can be thought of as geometric nonlinearity.

Material nonlinearity involving departure from Hooke's law occurs primarily through plasticity behavior for LWR components. At high levels of seismic excitation the difference between damping and material plasticity becomes somewhat academic since both are processes of energy absorption which will affect the dynamic response. Very large uncertainties in subsystem response are associated with nonlinearity as dynamic excitation is increased toward a point where failure may occur.

5.6.4 Decoupling and Boundary Conditions

By definition subsystems for SSMRP are identified as those pieces of equipment which are seismically qualified by decoupling them from the building and soil structure analysis. This decoupling process is done more for the purposes of economic and practical considerations than because there is no dynamic interaction. Decoupling is one of the major sources of uncertainty in subsystem response because the decoupling not only often changes the dynamic behavior of the equipment from that which it would exhibit in a coupled configuration, but decoupling also affects the definition of seismic input which the equipment will experience. It should be pointed out that if the input motions at the decoupling location were perfectly certain, and completely described, then there would be no decoupling or boundary condition uncertainty effect on the subsystem response. However, since there usually will be some significant approximation involved in the description of the input motions, it is expected that two forms of uncertainty need to be accounted for in the SSMRP analysis: a) changes to the input, b) changes to the response. Some observers believe that the overall error effect of decoupling will generally cause a conservative trend on the subsystem response prediction (Reference 17). We are,

to date, unable to substantiate this idea. For the purposes of this subsystem study effort only the b) item will be addressed since the a) item should be covered by another SSMRP project.

The boundary conditions are closely related to decoupling. All subsystems which are decoupled must assume some boundary conditions whether testing or analysis used to seismically qualify the equipment. These boundary conditions often involve the assumption of rigidity at some point where structures are not perfectly rigid. This source of uncertainty can often be minimized by use of in-situ testing to determine the actual frequencies of subsystems in their as-installed configuration. Therefore, if pure analysis or pure decoupled testing as used, there may be a significant source of subsystem response uncertainty due to incorrectly assessed boundary conditions.

5.6.5 Design Errors

Design errors are a source of subsystem response uncertainty which are always possible, but difficult to quantify. Such errors can occur regardless of the type of seismic qualification. The Quality Assurance procedures of the nuclear industry have as one objective the minimization of such design errors, but there is a limit to how well such errors can be eliminated. For the purposes of the SSMRP project it is important to recognize that such uncertainty exists and to structure the risk analysis so that design errors will be accounted for. The design errors are evaluated in this project by use of probability assignments developed from opinions of experts surveyed. The questionnaire asked each respondent to include all conceivable forms of uncertainty (page A-2) and suggested a checklist (page A-6) which specifically includes "errors".

5.6.6 Time Dependent Changes

Seismic qualification occurs somewhere in the design and construction process of a nuclear plant. It is well known that certain characteristics of seismic response may be influenced by processes which

are time dependent and cannot be fully simulated in the qualification stage. The typical sources for these time dependent changes are fatigue, aging, stress corrosion, flow growth, wear out, etc. All of these processes are complex and can cause the subsystem seismic response which may occur somewhere during the design lifetime of the plant to be different from that observed in the original seismic qualification. The quantification of these uncertainty influences can come from two sources 1) prior assignments (part of this study) and 2) specialized analysis which could be performed in Phase 2 if necessary.

5.7 Quantification of Subsystem Response Uncertainty

The sources of subsystem response uncertainty have been discussed in Section 5.6 and this section is devoted to providing a quantitative description of the response uncertainties for use in Phase 1 of SSMRP. The first question which must be addressed is how the uncertainty of response is to be defined. Two approaches have been considered, the first being a set of random variables applied to the subsystem transfer function as discussed in Section 3.3 and the second an overall random variable defined as follows:

$$K = \left| \frac{\text{Actual Seismic Response}}{\text{Predicted Seismic Response}} \right| \qquad (1)$$

The first approach is of course more comprehensive, because it allows one to separate the uncertainty affects of various inputs from those caused by the subsystem itself. However, the transfer function approach introduces considerable computational complexity in the SSMRP program which is not desirable. Therefore, the main effort in this project was focused on the overall uncertainty defined by equation (1).

The next question is, should the uncertainty in response be developed by first quantifying its overall effect and then determining its pieces, or

by developing the pieces which are combined in some fashion to obtain the total uncertainty? The latter approach is effective where detailed information on the pieces can be assembled into a representation of the total uncertainty. The difficulty with the synthesis approach is that the effect on the subsystem response uncertainty caused by individual sources is unknown unless the individual sources are propagated through the subsystem transfer function for the seismic inputs of concern. Take, for example, the generic uncertainty assignments provided by NSC concerning mass, stiffness, and damping in Section 5.6 of this report. The influence of these input uncertainties on the response of any particular subsystem will depend both on the subsystem transfer function and the time history inputs. This could be determined for any class of subsystems and inputs by Monte Carlo type analysis, but without the benefit of such analysis, it is difficult to assign response uncertainty due to each separate cause which would have any meaningful relationship to the original mass, stiffness, and damping uncertainty assignments. In view of this problem it was decided that for the SSMRP Phase 1 effort, emphasis should be placed on assigning the overall subsystem response uncertainty due to all causes shown in Table 5.6.1 and then develop a convenient algorithm to separate the individual effects. This makes the assumption that meaningful "prior" type probability assignments can be made by experienced seismic experts for the overall uncertainty more accurately than such experts could assign the separate causes and their interactions. We believe that this assumption is consistent with the present state of uncertainty information on K (equation (1)) held by many seismic experts.

5.7.1 Questionnaire

We designed an industry questionnaire to solicit "prior" type information from selected seismic experts as well as key NSC personnel concerning the random variable K defined by equation (1) using the currently available industry methods of seismic qualification as a

basis of response uncertainty. The term "prior" is used in a Bayesian sense to indicate that it is a subjective state of information assigned without the benefit of direct statistical data being available. The exact questionnaire used is reproduced in Appendix A. The industry participants who generously responded to our questionnaire are listed in Appendix B. The objective of the questionnaire was to develop prior probability functions for K in sufficient detail for each of the 18 categories of subsystems which were developed in Section 4 of this report and summarized in Table 4.1. Only 4 of the 18 sets were asked of any one expert (outside of NSC) so as to minimize the time required to respond. However, different groups of 4 sets were asked for each person so that all 18 sets had at least three respondants.

The basic information requested for the K function was at 4 values of K as can be seen from Figure 1b of Appendix A. Four values were selected so as to obtain a complete description of K including its distribution shape, mean, variances or standard deviation. The values were selected so as to obtain a quantitative uncertainty measure of both the conservatism (mean value less than $K = 1.0$) and possible non-conservatism caused by uncertainty at $K>>1.0$.

In addition to the K distribution, the questionnaire asked two more questions for each of the 18 sets of components to provide a prior data base for the relative effects of random versus modeling uncertainty as well as possible quantification of nonlinear effects. The relative random effects were measured by asking for the percentage of total uncertainty caused by random uncertainty (this distinction between random and modeling is somewhat arbitrary and for the purpose of the questionnaire was defined by Table 1 of Appendix A) as is graphically illustrated in Figure 2 of Appendix A. The nonlinear question requested a multiplier on uncertainty as caused by increasing response from the OBE allowable stress levels to the SSE allowable stress levels.

TABLE 5.7.1

RESULTS FROM APPENDIX A QUESTIONNAIRE

Set	$K = \overset{\%}{0.5}$	$K = \overset{\%}{1.0}$	$K = \overset{\%}{2.0}$	$K = \overset{\%}{3.0}$	Random $\frac{\overset{\%}{\sigma_r}(OBE)}{\sigma_{r+s}(OBE)}$	Nonlinear $\frac{\sigma_{r+s}(SSE)}{\sigma_{r+s}(OBE)}$
1	99,90,95 80,70,99,80 75,85	70,2,40 10,30,50,10 10,15	40,.2,1 1,1,1,5 2,3	20,.05,.5 .1,.1,0,1 .1,2	50,80,20 10,20,10,50 10,35	1.2,3.33,1.1 1.2,1.5,1.2,1.5 1.5,1.5
2	75,90,95,90 95	15,40,50,10 15	2,5,1,.1 .1	.5,1,.1,.01 0	0,25,1,30 5	1.05,1.5,3.0,3.0 1.2
3	75,99,80 99,90	5.3,10,2 50,50	1.3,5,.1 1,5	0,3,0 .1,1	0,10,5 20,10	.97,1.3,1.0 1.2,1.2
4	50,70,50 95,99,50,70	5,10,5 40,80,10,10	.5,1,1 10,40,.1,1	.05,.1,0 1,10,.01,1	10,10,57 60,1,10,60	1.5,1.3,1.0 1.0,1.0,1.2,1.2
5	60,70,85,95	25,60,50,30	2,30,5,5	.5,10,0,1	25,1,7,75	1.6,3.0,1.3,1.3
6	50,95,60	5,75,15	2,10,1	.1,.1,.1	20,5,10	1.0,1.0,1.2
7	65,80,90 60,100	30,20,20 40,50	5,3,10 20,0	.5,.3,.5 10,0	10,5,30 1,5	1.1,1.2,1.1 2.0,1.2
8	99,60,99,80 50	20,4,50,5 .1	10,.2,1,.05 .01	5,0,.1,.01 .001	10,10,20,30 0	1.3,1.0,1.1,1.5 1.3
9	50,85,99 100,99	20,30,50 50,5	1,2,.1 0,.1	.1,.2,.01 0,0	20,20,80 5,2	1.0,1.0,1.0 1.15,1.5
10	30,95,60,60	10,75,40,.1	1,50,2,.01	.1,35,.5,.001	10,1,20,15	1.5,4.0,3.0,1.4
11	99,80,20 99,100	5,1,3 50,50	3,.1,.5 .1,0	1,0,.01 .01,0	5,0,5 20,5	1.1,1.0,1.0 1.0,1.15
12	80,90,90,60 60	40,50,10,20 .5	5,15,.1,5 .05	.5,1,.01,3 .005	2,1,30,2 0	1.5,3.0,3.0,2.0 1.4
13	70,80,15 70,80,95	3,5,2 50,50,30	.3,.5,.3 30,3,5	.03,.05,.01 20,0,1	20,0,5 .1,8,75	2,1.0,1.0 4.0,1.4,1.3
14	95,10,90 90,95	40,1,20 50,1	10,.05,5 5,.05	1,.001,.5 1,.01	30,50,20 20,20	1.5,1.0,1.0 1.3,1.3

TABLE 5.7.1

RESULTS FROM APPENDIX A QUESTIONNAIRE

Set	$K = 0.5$ %	$K = 1.0$ %	$K = 2.0$ %	$K = 3.0$ %	Random $\frac{\sigma_r(\text{OBE})}{\sigma_{r+s}(\text{OBE})}$ %	Nonlinear $\frac{\sigma_{r+s}(\text{SSE})}{\sigma_{r+s}(\text{OBE})}$
15	70,70,75,70	65,30,18,10	60,7,5,2	30,2,.5,1	1,5,10,15	3.0,1.3,1.2,1.3
16	70,90,80,70	40,50,10,15	5,10,.1,3	.5,.1,.01,2	2,1,20,1.6	1.3,2.0,2.0,1.5
17	50,80,80 50,99,100	10,5,5 10,50,50	1,.5,.5 5,10,0	.1,.05,.05 0,1,0	20,20,0 0,1,5	1.6,1.2,1.0 1.5,3.0,1.3
18	95,80,70 80,95	15,5,50 10,30	5,.5,40 .1,5	1,.05,30 .01,1	25,0,.1 20,75	2,1.0,3.0 3.0,1.3

TABLE 5.7.2

Set	AVERAGED RESULTS FROM QUESTIONNAIRE % K = 0.5	% K = 1.0	% K = 2.0	% K = 3.0	Random $\frac{\%\ \sigma_r(OBE)}{\sigma_{r+s}(OBE)}$	Nonlinear $\frac{\sigma_{r+s}(SSE)}{\sigma_{r+s}(OBE)}$
1	85.9	26.3	6.0	2.6	31.7	1.56
2	89.0	26.0	1.64	0.32	12.2	1.95
3	88.6	23.5	1.48	0.82	9	1.13
4	69.1	22.9	7.66	1.73	29.7	1.17
5	77.5	41.2	10.5	2.88	27	1.51
6	68.3	31.7	4.33	0.1	11.7	1.07
7	79.0	32.0	7.6	2.3	10.2	1.32
8	77.6	15.8	2.25	1.02	14.0	1.24
9	86.6	31.0	0.64	.062	25.4	1.13
10	61.2	31.3	13.3	8.9	11.5	2.48
11	79.6	21.8	.74	.20	7	1.05
12	76	24.1	5.03	.90	7	2.18
13	68.3	23.3	6.52	3.52	18.0	1.78
14	76	22.4	4.0	.4	28	1.22
15	71.2	30.8	18.5	8.38	7.8	1.7
16	77.5	28.8	4.5	0.65	6.2	1.7
17	76.5	21.7	2.8	1.2	7.7	1.6
18	84.0	22.0	10.12	6.42	24.0	2.06

The response to the questionnaire is reported here as Table 5.7.1 in anonymous fashion because this was the agreed-upon format and because anonymity emphasizes the prior nature of the data. All raw data obtained from the questionnaire is contained in Appendix E.

5.7.2 Preliminary Data Reduction

The most important preliminary data reduction was judged to be an averaging of each redundant piece of information at the requested points. This averaging is performed in Table 5.7.2. Examination of Table 5.7.1 makes clear that widely variable judgments are held by industry experts expecially concerning the possible non-conservative region $K >> 1.0$. While Table 5.7.2 represents a best average judgement by the several experts, the results in Table 5.7.1 are so variable that the triad classification scheme was re-examined for possible simplification in the Phase 1 SSMRP effort. The differences between the results of most of the sets 1 to 18 are considerably smaller than the differences between expert judgments in any one set. This means that 18 sets of subsystems provides more potential resolution of differences between sets than can be justified by our present state of prior information. Therefore, the 18 sets of Table 5.7.2 can be reduced to 3 to 5 larger sets for the purposes of Phase 1 of the SSMRP study without any significant loss of prior uncertainty information. The following Table 5.7.2.1 illustrates 3 supersets as a proposed simplification.

TABLE 5.7.2.1

Superset 1 Small Uncertainty		Superset 2 Intermediate Uncertainty		Superset 3 Large Uncertainty	
Set#	Key Characteristics	Set#	Key Characteristics	Set#	Key Characteristics
1	Complex, linear analysis, RRS	2	Nonlinear, test, broad band		
3	Complex, linear, test, narrow band	4	Linear, Complex, equivalent static	10	Nonlinear, simple, equivalent static
7	Simple, linear analysis RRS	5	Nonlinear, test broad band	15	Nonlinear, simple, analysis, T.H.
8	Complex, linear test, broad band	6	Linear, simple, equivalent static	18	Nonlinear, test, PSD
9	Linear, rigid, equivalent static	12	Nonlinear, complex, test narrow band		
11	Linear, rigid, test, broad band	13	Nonlinear, test broad band		
14	Simple, linear, analysis, RRS	16	Nonlinear, in-situ test, analysis, RRS		
17	Nonlinear, rigid, test, broad band				

Table 5.7.2.1 was developed by ranking the generic triad classification for each set according to the overall response uncertainty behavior which might be expected especially at higher K values. The grouping in Table 5.7.2.1 does not in all cases exactly agree with a simple numerical ranking of results of tables 5.7.1 and 5.7.2, but the trend is consistent. This suggests that after the actual inventory for Zion is performed and classified, a simplification along the lines indicated by Table 5.7.2.1 should be performed. If we use the data of Table 5.7.2, but average the total data points within each superset, the following simplified results are obtained in Table 5.7.2.2.

TABLE 5.7.2.2

SIMPLIFIED CLASSIFICATION SCHEMES
FOR PHASE 1 OF SSMRP

Superset	K% = .5	K% = 1.0	K% = 2.0	K% = 3.0	random $\frac{\sigma_r(OBE)}{\sigma_{r+s}(OBE)}$	nonline $\frac{\sigma(SSE}{\sigma(OBE}$
1	81.2	24.3	3.18	1.07	16.6	1.28
2	75.1	28.3	5.74	1.44	16.0	1.62
3	72.1	28.0	14.0	7.9	14.4	2.08

5.7.3 Separating Individual Uncertainty Effects

This section is intended to outline a procedure to identify separately the contribution to subsystem response uncertainty caused by individual items in Table 5.6.1. This information is needed for sensitivity studies so that research activities of SSMRP can be focused on sources of uncertainty which have a significant effect on seismic risk.

The following algorithm is proposed. Assume that the overall K random variable identified previously is made up of a series of 9 factors as follows:

$$K = K_m * K_k * K_d * K_\Delta * K_t * K_n * K_b * K_e * K_c \qquad (1)$$

where K has a probability distribution which is log normal and the 9 K_i independent product factors are also log normal. The individual 9 K_i factors are intended to represent the following contributions to overall subsystem response uncertainty.

	Uncertainty Effect
K_m	Mass magnitude and distribution
K_k	Stiffness magnitude and distribution
K_d	Damping magnitude and distribution
K_Δ	Discretization
K_t	Theory, beam, shell, 3D, test
K_n	Nonlinear, geometric, material
K_b	Decoupling and boundary conditions
K_e	Design errors
K_c	Changes with time, stress corrosion, etc.

All values of K_i can be assumed to have a mean value of 1.0 except K_d, K_n, K_b, and K_c. The K_d, K_n, and K_b values can generally be expected to have values of <1.0 because they are the chief sources of conservatism which cause the actual response to be smaller than the predicted response. K_c would normally be expected to have a value of >1.0 since it is likely to cause a non-conservative effect.

First we will address how the random and modeling uncertainties can be separately identified from the data generated in the questionnaire. Since mean value of K_m and K_k are unity, then the mean value of the random uncertainty will be

$$\bar{K}\ (\text{random}) = \bar{K}_m * \bar{K}_k = 1.0 \qquad (2)$$

It can be shown that K_n independent log normal distributions have the characteristic such that if

$$K = K_1 \, K_2 \, K_3 \cdots K_n \tag{3}$$

then the means and standard deviations of the individual K_i's are related to the overall mean and standard deviation as follows

$$\bar{K} = \bar{K}_1 * \bar{K}_2 * \bar{K}_3 \cdots \bar{K}_n \tag{4}$$

$$\frac{s}{K} = \left[\left[\left(\frac{s}{K_1} \right)^2 + \left(\bar{K}_1 \right)^2 \right] * \left[\left(\frac{s}{K_2} \right)^2 + \left(\bar{K}_2 \right)^2 \right] * \cdots \left[\left(\frac{s}{K_n} \right)^2 + \left(\bar{K}_n \right)^2 \right] - \left(\bar{K}_1 * \bar{K}_2 * \cdots \bar{K}_n \right)^2 \right]^{\frac{1}{2}} \tag{5}$$

where $\overset{s}{K}$ is the standard deviation of the product K and $\overset{s}{K}_i$ is the standard deviation of each K_i.

From the questionnaire data we can obtain a best fit to both the standard deviation of K and the mean of K so that

$$\overset{s}{K} \text{ (random)} = \frac{\sigma_{r \text{ (OBE)}}}{\sigma_{r+s \text{ (OBE)}}} * \text{(best fitted standard deviation for prior K)} \tag{6}$$

$$\bar{K} \text{ (model)} = \text{(best fitted mean for prior K)} \tag{7}$$

Use of equation (5) allows us to express the overall standard

deviation, $\overset{s}{K}$, as a function of random and model parameters as follows:

$$\left(\overset{s}{K}\right)^2 = \left[\left[\overset{s}{K}\ (\text{random})\right]^2 + \left[\bar{K}\ (\text{random})\right]^2\right] * \left[\left[\overset{s}{K}\ (\text{model})\right]^2 + \left[\bar{K}\ (\text{model})\right]^2\right] - \left[\bar{K}\ (\text{random})\right]^2 * \left[\bar{K}\ (\text{model})\right]^2 \qquad (8)$$

Solving equation (8) for $\overset{s}{K}$ (model) and using equation (2) yields

$$\overset{s}{K}\ (\text{model}) = \sqrt{\frac{\left(\overset{s}{K}\right)^2 + \left[\bar{K}\ (\text{model})\right]^2}{\left[\overset{s}{K}\ (\text{random})\right]^2 + 1} - \left[\bar{K}\ (\text{model})\right]^2} \qquad (9)$$

Therefore the random and modeling uncertainty parameters are given by equations (2), (6), (7), and (9).

Similarly, if relative values for uncertainty parameters of the terms in equation (1) can be assigned or determined, equations (4) and (5) can be used to provide consistency between overall K uncertainty and its constituent parts. This procedure can be used with data fits for the 18 sets or 3 supersets of prior distributions determined in this report (data of Tables 5.7.2 and 5.7.2.2).

5.7.4 Improving the Prior Uncertainty Data

There are several possible ways to improve the subsystem response uncertainty information generated in this report. The most direct would be to obtain actual test data or simulated test data which measures at least some of the K_i values which contribute to K. Bayes Theorem can be used to combine actual data with the prior information and produce an improved posterior probability for several of the uncertainties. This could prove unreasonably expensive if subsystem response were the only motivation for testing, but if other seismic effects require a major experimental program, then subsystem response data could be obtained as a by-product.

Another approach to improve the uncertainty information would consist of developing specialized analysis of selected subsystems which would permit Monte Carlo type uncertainty studies to identify more specifically several of the K_i influence. Again Bayes theorem can be used to combine the prior distribution with data obtained from special analysis much as if the special analysis represents simulated test data.

The need for the improvement of the prior subsystem response uncertainty of course depends on the results of the proposed Phase 1 SSMRP sensitivity studies.

5.8 Computer Programs for Subsystem Response

Computer programs for performing subsystem seismic dynamic analysis are many and a comprehensive review of those generally available is beyond the scope of this subsystem response project. However, a summary is provided in Table 5.8.1 to outline the general capabilities available with some of the more important computer programs in general use.

Four of the computer programs which are specially designed for piping analysis have been further broken down according to their more detailed capabilities and are illustrated in Table 5.8.2.

TABLE 5.8.1

INDUSTRY COMPUTER PROGRAMS FOR
SEISMIC SUBSYSTEM RESPONSE ANALYSES

1. ADLPIPE - Arthur D. Little Company

   Static, dynamic (response-spectrum and T/H) analysis of piping systems, extensive plotting capability.

2. TRIFLEX - AAA Technology

   Piping analysis and compliance with established codes.

3. NUPIPE - Nuclear Services Corporation

   Thermal, static, dynamic (R.S. and T/H) analysis of Class I piping systems in conformance with ASME Section III multiple support excitation capability.

4. PIPESD - URS/John A. Blume & Associates

   Static, dynamic and thermal analysis of piping systems in conformance with established piping codes.

5. ANSYS - Swanson Engineering Analysis

   Large scale general purpose finite element program for linear and nonlinear static, dynamic analysis, steady-state and transient heat transfer analysis and other special analysis, e.g., substructures, coupled heat transfer-fluid flow, etc.

6. EASE2 - Engineering Analysis Corporation

   Linear static and dynamic structural analysis, plotting capability.

TABLE 5.8.1

(Continued)

7. MARC - MARC Analysis Research Corporation

   General purpose finite element program for linear and nonlinear static and dynamic analysis of structures.

8. NASTRAN - MacNeal-Schwendler Corporation (MSC version)

   Largest general purpose finite element program in use today. Static; thermal; dynamic analysis to deterministic and random loads; steady-state heat transfer; fluid-structure interaction, etc.

9. PISCES - Physics International

   A system of finite-difference codes to study interaction of fluids, solids, and structures under a wide variety of dynamc and static loading conditions; linear as well as nonlinear.

10. SUPERB - Structural Dynamics Research Corporation

    A general purpose finite element program for static and dynamic analysis of structures.

11. STARDYNE - Mechanics Research Institute, Incorporated

    A general purpose finite element program for linear thermal, static, and dynamic analysis under deterministic and stationary random loads.

12. DANUTA - Allis-Chalmers Corporation

    Static, thermal, dynamic analysis of 2-D and 3-D structures.

TABLE 5.8.1

(Continued)

13. NISA - Engineering Mechanics Research Corporation

General purpose finite element program for static and dynamic analysis, heat transfer analysis and analysis of special field problems.

14. SAP IV - University of California, Berkeley

Thermal, static, dynamic linear analysis of one, two, and three dimensional structures.

15. STRUDL/DYNAL - Massachusetts Institute of Technology

Static and dynamic analysis of framed and continuous structures.

16. STAGS - Lockheed, Palo Alto Research Laboratory

Finite difference code for analysis (nonlinear collapse, buckling, etc.) of general shells.

17. SPAR - Engineering Information Systems, Incorporated

Stress, buckling and vibration analysis of linear finite element systems.

18. NIFDI - Prototype Development Associates, Incorporated

Nonlinear analysis of interfaces with friction between discontinuous solids having interference fit.

19. PIPDYN II - Franklin Institute Research Laboratories

Static, thermal, and dynamc analysis of piping systems with ASME Code compliance.

TABLE 5.8.1

(Continued)

20. ASHSD - University of California, Berkeley

    Static and dynamic analysis of shells and solids of revolution.

21. PIPERUP - Nuclear Services Corporation

    Dynamic nonlinear response of piping to blowdown forces.

22. ADINA - Massachusetts Institute of Technology

    A general purpose nonlinear analysis (static and dynamic) of structural systems.

23. NONSAP - University of California, Berkeley

    A finite element computer program for static and dynamic analysis of nonlinear systems.

24. FELAP - Franklin Institute Research Laboratories

    Static, thermal, and dynamic analysis of arbitrary structures.

25. DYPLAS - Franklin Institute Research Laboratories

    Static, dynamic elasto-plastic-creep analysis programs for structural systems.

26. BOSOR - Available through MCAUTO and ISD

    Stress, stability, and vibration analysis of shells of revolution; includes large displacement and creep.

TABLE 5.8.2

PIPING COMPUTER PROGRAMS DETAILED CAPABILITY

	ADLPIPE	PIPDYN II	PIPESD	NUPIPE
1. Preprocessing				
Input Data Check	x		x	x
Geometry Plotting	x	x		x
2. Modeling				
Straight Pipe	x	x	x	x
Elbow	x	x	x	x
Tees	x	x		
Boundary Springs	x	x	x	x
Special Elements	x	x		
3. Loading				
Static - Thermal	x	x	x	x
Deadweight	x	x	x	x
Applied Loads	x	x	x	x
Dynamic - Response Spectra - Single Input	x	x		x
Multiple Input				x
Seismic Time History - Single Input	x	x		x
Multiple Input				x
Applied Loads				x
4. Analysis Methods				
Response Spectrum	x	x	x	x
Mode Superpositions	x	x		x
Direct Integrations				
5. Code Compliance				
Nuclear Power Piping	x	x	x	x
ASME Sec. III - Class I	x	x	x	x
Class II	x	x	x	x
Class III	x			x
6. Post-Processing				
Plotting - Static Displacements		x		
- Mode Shapes	x	x		
- Stress Histories	x			

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APPENDIX A

QUESTIONS BEING ASKED - BACKGROUND

As part of the Seismic Safety Margins Research Program (SSMRP), we have grouped a number of nuclear safety-related components or equipment which may have common response uncertainty characteristics into sets. We are asking you to examine 4 of these sets and to assign 6 uncertainty numbers to each set which reflects your estimate of the component or equipment seismic response prediction uncertainty when using currently available industry methods of seimsic qualification. Since we are asking for 6 uncertainty numbers for each of the 4 sets of components, your answers to these questions will consist of a total of 24 numbers. You will find 6 blank boxes for your answers in each of the 4 question sheets at the end of this explanation.

All of the questions concern a dimensionless K factor defined as follows:

$$K = \left| \frac{\text{Actual Seismic Response}}{\text{Predicted Seismic Response}} \right| \qquad (1)$$

By seismic response we mean the specific qualification parameter such as the primary stress which may be induced by an earthquake. Since many components can be expected to exhibit nonlinear behavior, expecially at higher postulated seismic levels, and since many qualification procedures are based on linear analysis, the K factor as defined by equation (1) may vary with the seismic excitation level. In order to eliminate this source of variation in your answers, we are asking you to focus on the OBE level of stress which is typically permitted in the components. The first four uncertainty numbers for each of the 4 sets of components represent probability values at 4 specific K ratios where the seismic input is known for certain, and where the predicted response is at the OBE allowable stress level. Figure 1(b) is a complimentary cumulative distribution function (CCDF) which is a convenient graphical form to think about the questions and to quantify your answers. What the CCDF

curve means is that for each K value on the abscissa, the ordinate is the probability that K is greater than the stated value. Large K values compared to 1.0 mean that the actual seismic response is greater than the predicted seismic response (non-conservative) and conversely small K values compared to 1.0 mean that actual response is less than the predicted response (conservative).

The CCDF curve monotonically decreases with increasing values of K and you are asked to provide probability values at K = 0.5, 1.0, 2.0, and 3.0. You may recall that the more familiar probabiliy density function (PDF) shown in Figure 1(a) is related to the CCDF curve of Figure 1(b) by a relationship:

$$PDF\ (K) = -\frac{d}{dK}\ [CCDF(K)] \qquad (2)$$

so that once the CCDF curve is defined, then a PDF curve can also be determined.

Now comes the hard part! When you assign your four probability values for each set of components, please include <u>all conceivable forms of uncertainty</u> which can make the actual seismic response different from the predicted seismic response. As an aid to reminding you of things which can cause the actual response to be different from the predicted response, Table 1 should be examined. Table 1, Subsystem Seismic Response Uncertainty, lists 12 individual items in two columns headed "Random" and "Systematic". These two terms, "Random" and "Systematic", may have slightly different meanings in various parts of the SSMRP program, but for our purposes here that is not important. What is important is that when you assign your 4 probability numbers at the OBE stress level, you <u>include the total contribution to uncertainty caused by all 12 items in Table 1</u>. You may feel that you do not have enough information to accurately assess all items in Table 1, but you are being asked only to apply your best overall judgement to this difficult question.

After you have assigned the 4 CCDF numbers the hard part is over, but while your mind is in this somewhat uncomfortable but creative position, we want you to assign two more numbers to each set of components. The first of these can be conceptually understood by looking at Figure 2. Figure 2 is a PDF curve similar to Figure 1(a) where only 4 of the 12 uncertainty items of Table 1 have been included. These 4 are the so-called random effects only. Figures 1(a) and 2 illustrate a standard deviation value, σ_{r+s}, for all 12 uncertainties of Table 1, and a standard deviation, σ_r, values for only the 4 so-called random of the 12. You may recall, a standard deviation is a function of the shape of any PDF curve and is equal to the square root of the variance. The standard deviation is a measure of the gross uncertainty present and represents graphically the aspect ratio or width to height ratio of the PDF curve. What you are being asked in box 5 is what fraction of the total response uncertainty is caused by the random items in Table 1.

You do not need to draw the PDF curve nor estimate σ_{r+s} corresponding your Figure 1(b) answers in order to answer this question. You can simply answer the question "What portion of the total uncertainty caused by the 12 items in Table 1 can be attributed to the 4 random items?" The standard deviation discussion is only background information to explain more fully the significance of the question.

The sixth number for each set of components is similar to the fifth and is conceptually illustrated in Figure 3. The purpose for the sixth number is to solicit your judgement for possible nonlinear effects by asking you to assign a standard deviation ratio for the SSE level compared with how you would expect it to be at the OBE level. If in your judgement the actual response is truly linear at the SSE level, then

$$\frac{\sigma_{r+s(SSE)}}{\sigma_{r+s}(OBE)} = 1.0.$$

Therefore, the larger you assign this factor, the higher the effect of nonlinearity on uncertainty of response, i.e., a factor of 2.0 means that uncertainty of response is 2 times as large at the SSE levels as compared with the OBE level. Again it is not necessary for you to actually draw the PDF curve to answer this question. You can simply answer the question, "How will the effects of nonlinearity increase the overall uncertainty as the response increases from the OBE to the SSE levels expressed as a single multiplier on uncertanty?"

The following 4 sets of components are identified and provided with 6 blanks per set. Please assign numbers to the blanks.

Thank you.

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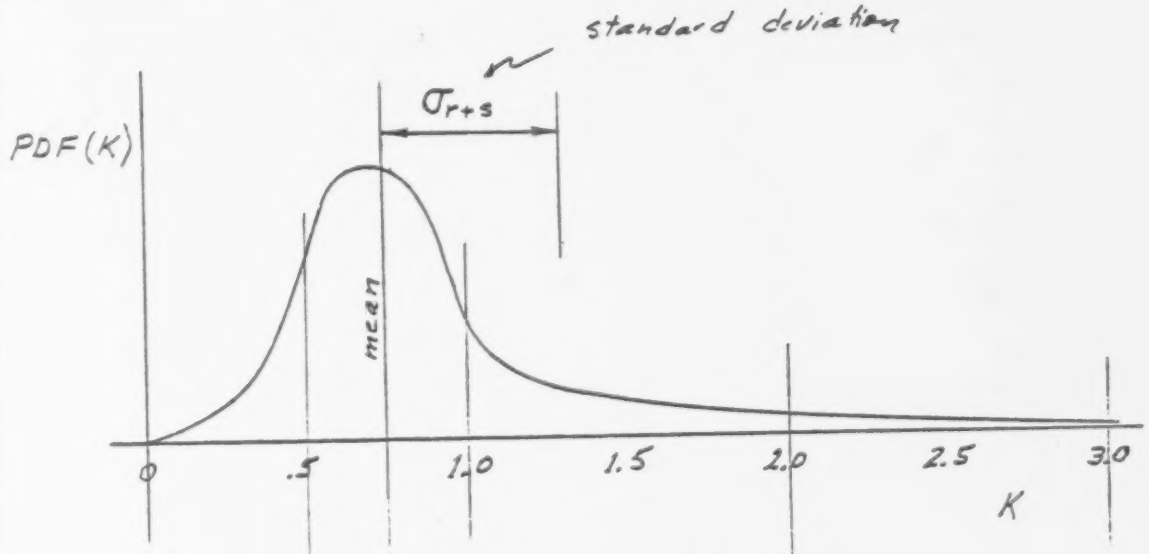

Figure 1a

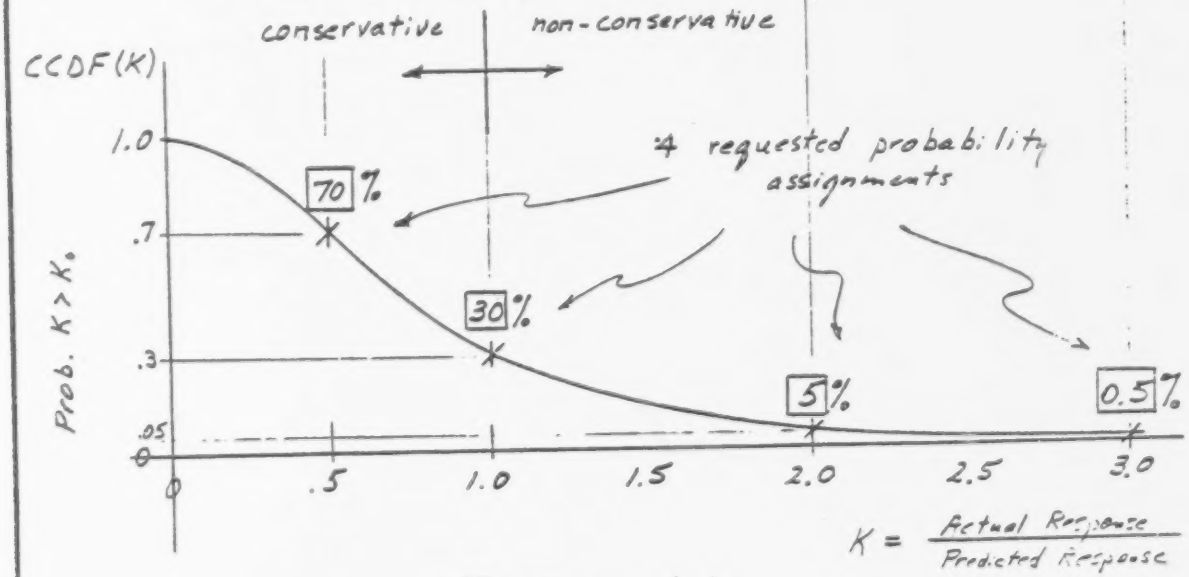

Figure 1b

Subsystem Response K Factor for Random and Systematic Uncertainty

TABLE 1

SUBSYSTEM SEISMIC RESPONSE UNCERTAINTY σ_{r+s}

RANDOM (FUNDAMENTAL) σ_r	SYSTEMATIC (MODELING) σ_s
MASS MAGNITUDE	DAMPING MAGNITUDE
MASS DISTRIBUTION	DAMPING DISTRIBUTION
STIFFNESS MAGNITUDE	DISCRETIZATION
STIFFNESS DISTRIBUTION	THEORY (BEAM, SHELL, 3D, TEST)
	NON-LINEARITY
	DECOUPLING & BOUNDARY CONDITIONS
	ERRORS
	TIME DEPENDENT CHANGES

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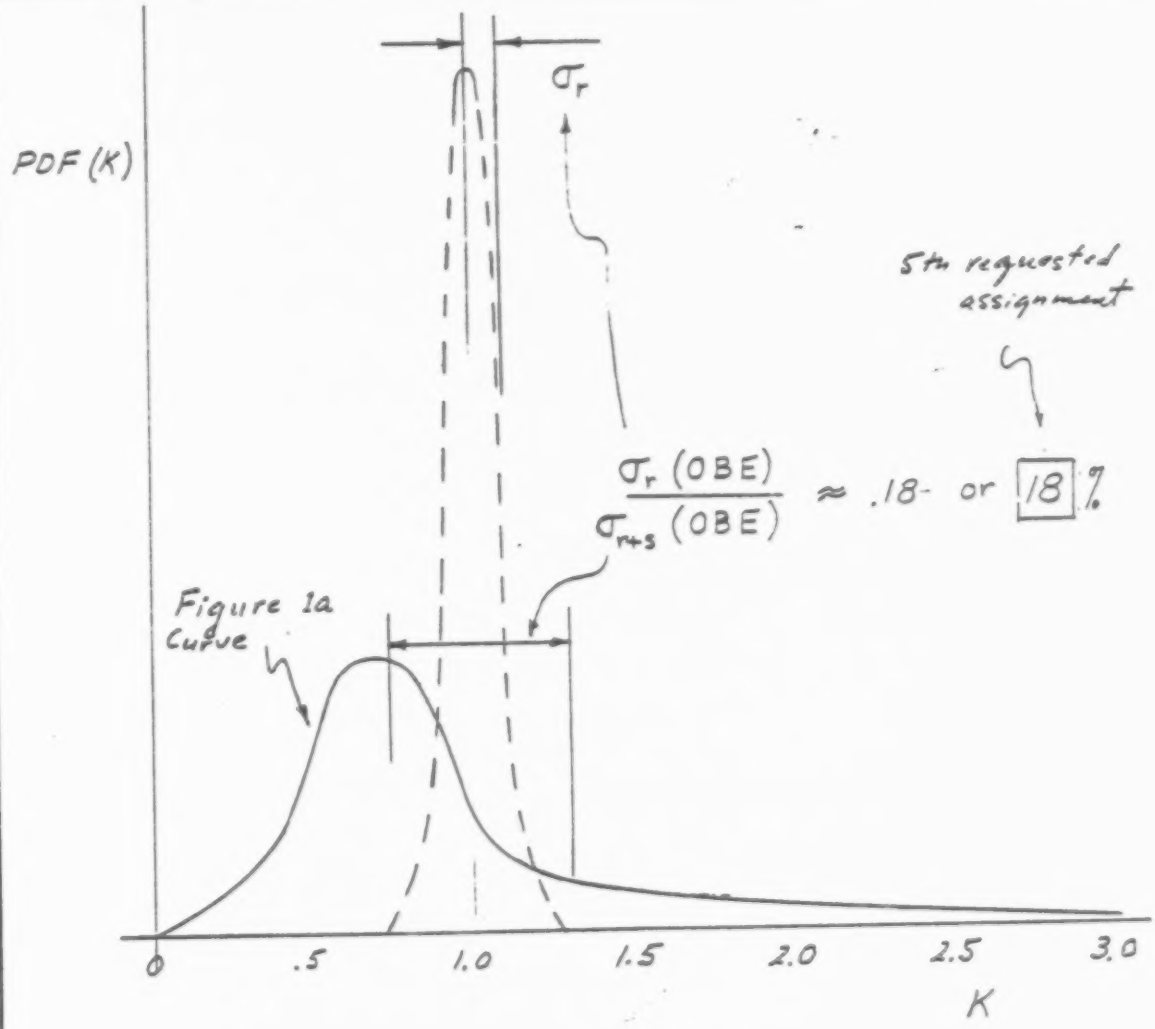

Figure 2

Subsystem Response K Factor for Random Uncertainty Only at OBE Allowable Stress Level Is the Dashed Curve

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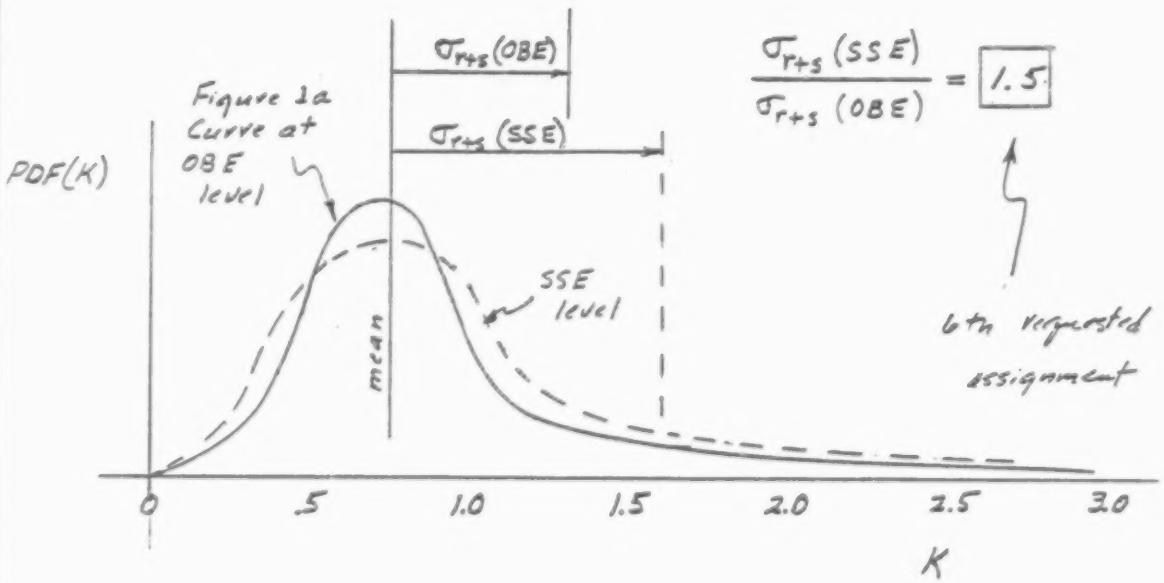


Figure 3

Subsystem Response K Factor for Total Uncertainty Illustrating Nonlinear Effects

QUESTION SHEET SET ☐

See Appendix D for wording used in each of 18 question sets

This set of components consists of those whose behavior can be characterized by *

The set of components is assumed to be seismically qualified by

The seismic response parameter which is assumed to be used for those components is

Typical components which we have put in this response classification are:

Please provide numbers for the missing blanks:

	$P(K>K_0)$	
Probability Actual Response is greater than 0.5 times predicted response	☐	%
Probability Actual Response is greater than 1.0 times predicted response	☐	%
Probability Actual Response is greater than 2.0 times predicted response	☐	%
Probability Actual Response is greater than 3.0 times predicted response	☐	%

Fractional part of uncertainty due to random effects (see Table 1)	$\frac{\sigma_r(OBE)}{\sigma_{r+s}(OBE)}$ ☐	%
Uncertainty Multiplier for nonlinear effects	$\frac{\sigma_{r+s}(SSE)}{\sigma_{r+s}(OBE)}$ ☐	

* See next page for clarification of terms

Meaning Of Terms Used In Subsystem Classification

Simple vs. Complex - These terms are used to differentiate structures whose major seismic response is expected to be in a single fundamental mode as compared with one where major response may be a result of modes other than the fundamental lowest mode.

Rigid vs. Flexible - These terms are used to differentiate structures which have no modes below 35 H_Z compared with those which do.

Nearly Linear vs. Significantly Nonlinear - These terms are used to differentiate structures where response is within ±20% of linear compared with those where nonlinearity is more than ±20%.

Compound Nonlinearity - This term is used to indicate both significant geometric and significant material nonlinearity in the same structure.

Required Response Spectrum - This term is used here to define the input response spectrum for the component or equipment and is assumed to have no uncertainty.

Narrow Band or Broad Band - These terms are used to differentiate seismic inputs for shake table qualification which are nearly sinusoidal having a single dominant response spectrum peak as compared with seismic inputs which have more than one major peak or are random.

Peak Stress vs. Primary Stress - These terms are the same as those used in the ASME Section III Code.

Multistate Severity Parameter - This term indicates that the component or equipment response has been characterized by two or more parameters, any of which could be critical at a failure level. An example would be that both the deflection and the primary stress could be critical so that both parameters have been characterized as part of the response.

best copy available

Binary Operability - When a shake table test is used to seismically qualify a piece of equipment where the response terms deformation or stress are of no direct interest, then operability or lack of operability (binary) is the only response quantity of significance. In this case response uncertainty is limited to the precision with which operability or non-operability can be measured at any particular level of seismic input.

APPENDIX B

INDUSTRY EXPERTS* WHO CONTRIBUTED
TO THE RESPONSE OF THE NSC QUESTIONNARIE

Outside NSC Participants:

Dr. George Bohm - Westinghouse Electric Company
Dr. Chang Chen - Gilbert & Associates
Mr. Norm Goldstein - Stone & Webster
Mr. Asa Hadjian - Bechtel
Dr. Robert Kassawara - Combustion Engineering
Mr. Parks Cobb - Duke Power Company
Dr. Jim Johnson - Lawrence Livermore Laboratory
Dr. Lun Liu - General Electric
Mr. Ahmed Meligi - Sargent & Lundy
Mr. George Shipway - Wylie Laboratories
Dr. John Stevenson - Woodward-Clyde
Mr. Ron Wray - Teledyne

NSC Participants:

Dr. Quasi Hossain
Dr. Maharaj Kaul
Mr. Richard Koppe
Mr. Sam Tagart, Jr.
Dr. Henry Thailer

*These experts were asked to respond in their own professional opinion and their answers do not necessarily represent replies of their affiliated organization.

APPENDIX C

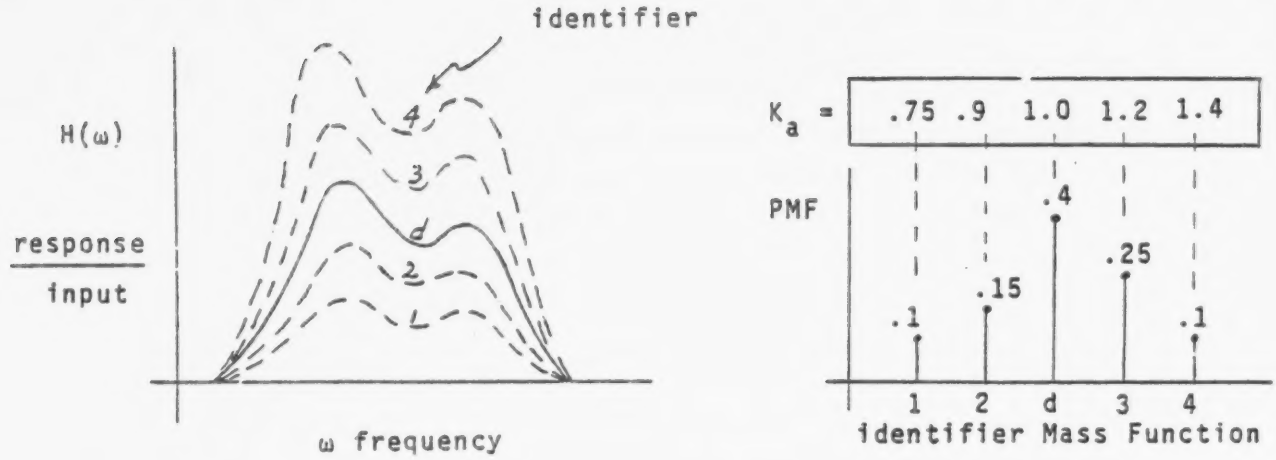
TRANSFER FUNCTION UNCERTAINTY

In order to more clearly illustrate the recommended concept involving the correlated transfer function uncertainty, Figure C is shown. We observe that the deterministic transfer function is identified by "d", and that the multiplier K_a permits scaling the deterministic transfer function curve along the ordinate direction, while the multiplier K_ω permits scaling the curve along the abscissa direction.

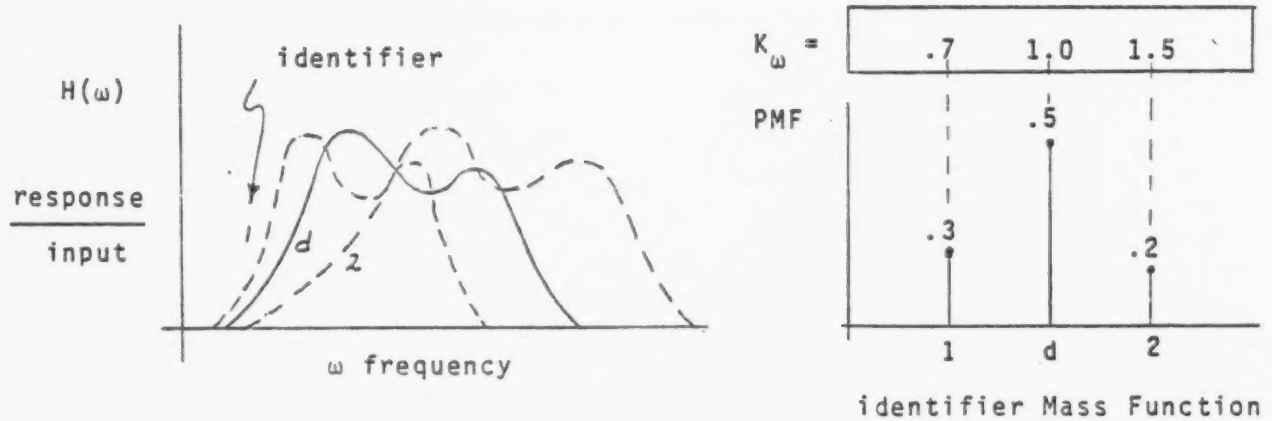
For selected values of K_a ranging from <1.0 to >1.0, a Probability Mass Function is assigned for discrete values of K_a and K_ω. The numbers of values for K_a and K_ω are somewhat arbitrary and depend on the resolution desired.

The chief advantage in this approach is that it permits a more realistic assessment of the way individual uncertainty influences will contribute to overall subsystem response uncertainty than the overall K factor approach, but it will generally be necessary to perform the comparison on a simplified subsystem. It is recommended that this correlated transfer function approach be further developed as an aid to understanding how individual K_i uncertainty effects contribute to the overall K uncertainty. It can be used to verify what may otherwise be a more subjective breakdown of uncertainty causes.

CORRELATED TRANSFER FUNCTION UNCERTAINTY $H'(\omega) = K_a * H\left(\frac{\omega}{K_\omega}\right)$



AMPLITUDE FACTOR, K_a



FREQUENCY FACTOR, K_ω

FIGURE C

APPENDIX D

Set 1

SUMMARY OF CLASSIFICATION FOR CRITICAL COMPONENTS FOR SUBSYSTEM RESPONSE

CLASSIFICATION IDENTIFICATION ON QUESTIONNAIRES (APPENDIX A) →

- 1.2 Nearly Linear - Complex Flexible Structure
- 2.1 Linear Dynamic Analysis with Required Response Spectrum
- 3.4 Max Primary Stress

Intake Structure
Ice Condenser Suppression Structure
Water Chillers
Tube Sheets (Heat Exchanger)
Shells (Heat Exchanger)
Water Boxes (Heat Exchanger)
Case and Attachments (Heat Exchanger)
Pressurized Tanks and Vessels
Accumulators
Line Surge Tanks
H & V Filters including HEPA
HEPA and other Filter Cases
Plates (Equipment Supports)
Large welded piping segments (pressurized) or fittings > 6" OD
Small welded piping segments (pressurized) or fittings ≤ 6" OD
Unpressurized piping and fittings (all sizes)
Platforms
H & V Ducts
Transformers (4 kV and 480V)
Cable Trays
Core Barrel (Reactor Component)
Jet Pumps (Reactor Component)
Sparagers (Reactor Components)
Air Coolers

24 items

TYPICAL COMPONENTS IDENTIFIED IN QUESTIONNAIRE OF APPENDIX A →

- Welded pipe segments
- Pressurized tanks
- Platforms

Set 2

CLASSIFICATION IDENTIFICATION ON QUESTIONNAIRES (APPENDIX A) →

1.5 Significant Geometric Non Linearity, Complex & Flexible

2.6 Shake Table Biaxial Test, broad band Required Response Spectrum

3.1 Max Input Acceleration (Response is binary operability)

Stemmed Valves
Relief Valves
Swing Check Valves
Duo Check Valves
Pressure Regulating Valves
Panels (Electrical)
Switchgear
Motor Control Centers
Cable Strain Relievers
Controllers (Instrumentation)
Electro-mechanical relays
Electrical Power Monitors

12 items

TYPICAL COMPONENTS IDENTIFIED IN QUESTIONNAIRE OF APPENDIX A →

Check valves
Pressure regulating valves
Electro-mechanical relays

Set 3

CLASSIFICATION IDENTIFICATION ON QUESTIONNAIRES (APPENDIX A) →

1.2 Nearly linear complex flexible structure

2.5 Shake Table Biaxial Test, narrow band Required Response Spectrum

3.1 Max Input Acceleration (Response is Binary Operability)

Large Horizontal Centrifugal Pumps
Vertical Centrifugal Pumps
Fractional HP Motors
Limitorque motors
Cooling fans mounted to structures
Fan Coil Units (Includes fans and coils)
Cooling fans internal to ducts
Pull Boxes
Motor Generators
Transducers (Instrumentation)

10 items

TYPICAL COMPONENTS IDENTIFIED IN QUESTIONNAIRE OF APPENDIX A →

Cooling fans
Centrifugal pumps
Small motors

Set 4

CLASSIFICATION IDENTIFICATION ON QUESTIONNAIRES (APPENDIX A) →

1.2 Nearly linear complex flexible structure

2.3 Equivalent Static Analysis with Required Response Spectrum

3.4 Max Primary Stress

Reactor Coolant Pump (PWR) seals and pressure boundary
Reactor Coolant Pump Rotor
Recirculation Pump (BWR) pressure boundary
Small Tubing (Air lines and instrument sensing)
Large Tubing (generally instrument sensing)
Sensing Lines
Tubing (Equipment Supports)
Pipe restraints

8 items

TYPICAL COMPONENTS IDENTIFIED IN QUESTIONNAIRE OF APPENDIX A →

Pump rotor
Pump case
Instrument tubing

Set 5

CLASSIFICATION IDENTIFICATION ON QUESTIONNAIRES (APPENDIX A) →

1.4 Significant Geometric Non Linearity simple and flexible

2.6 Shake Table biaxial test broad band Required Response Spectrum

3.1 Max Input Acceleration (Response is binary operability)

Ball Check Valves
Large Switches (Electrical)
Pushbutton Switches
I & C Switches
Level Probes (Sensor)
Indicating Gauges
Annunciator
Neutron Flux Monitors
Position Switches (Sensor)

9 items

TYPICAL COMPONENTS IDENTIFIED IN QUESTIONNAIRE OF APPENDIX A →

Electrical Switches
Annunciators

Set 6

CLASSIFICATION IDENTIFICATION ON QUESTIONNAIRES (APPENDIX A) →

1.1 Nearly Linear, Simple Flexible Structure

2.3 Equivalent Static Analysis with Required Response Spectrum

3.4 Max Primary Stress

Parting Walls
Floors and Ceilings
Tube Supports (Heat Exchanger)
Strainers (Integrity)
Crane Rails
Pipe Hangers
Battery Cell Rack

7 items

TYPICAL COMPONENTS IDENTIFIED IN QUESTIONNAIRE OF APPENDIX A →

Crane rails
Parting walls

Set 7

CLASSIFICATION IDENTIFICATION ON QUESTIONNAIRES (APPENDIX A) →

1.1 Nearly Linear, Simple Flexible Structure

2.1 Linear Dynamic Analysis with Required Response Spectrum

3.4 Max Primary Stress

Windows
Shafts
Couplings
Tubes (Heat Exchanger)
Large Beam (Equipment Supports)
Unistrut (Equipment Supports)
Control Rod Guides

7 items

TYPICAL COMPONENTS IDENTIFIED IN QUESTIONNAIRE OF APPENDIX A →

Heat Exchanger Tubes
Control Rod Guides

Set 8

CLASSIFICATION IDENTIFICATION ON QUESTIONNAIRES (APPENDIX A) →

1.2 Nearly Linear complex flexible structure

2.6 Shake Table Biaxial Test with broad band Required Response Spectrum

3.1 Max Input Acceleration (Response is binary operability)

Small Horizontal Centrifugal Pumps
Junction and Terminal Boxes
Cabinets (Electrical)
Lighting
Indicating Lights (Instrumentation)
Solid State Logic Boards
Radiation Monitors

---

7 items

TYPICAL COMPONENTS IDENTIFIED IN QUESTIONNAIRE OF APPENDIX A →

Electrical cabinets
Solid state logic boards

Set 9

CLASSIFICATION IDENTIFICATION ON QUESTIONNAIRES (APPENDIX A) →

1.3 Nearly linear and rigid

2.3 Equivalent Static Analysis with Required Response Spectrum

3.4 Max Primary Stress

Reactor Coolant Pump (PWR) fly wheel
Piping Penetrations
Pads (equipment support)
Pipe and tubing guides
Pipe and tubing supports
Core supports (gussets, etc.)
Spacers (Reactor Components)

7 items

TYPICAL COMPONENTS IDENTIFIED IN QUESTIONNAIRE OF APPENDIX A →

Piping penetrations
Core supports, gussets

- -

Set 10

CLASSIFICATION IDENTIFICATION ON QUESTIONNAIRES (APPENDIX A) →

1.4 Significant Geometric non linearity simple and flexible

2.3 Equivalent Static Analysis with Required Response Spectrum·

3.4 Max Primary Stress

Cranes
Hoists
H & V Louvers
Power Cables
I & C Cable

5 items

TYPICAL COMPONENTS IDENTIFIED IN QUESTIONNAIRE OF APPENDIX A →

Cranes
Power cables

Set 11

CLASSIFICATION IDENTIFICATION ON QUESTIONNAIRES (APPENDIX A) →

1.3 Nearly linear and rigid

2.6 Shake Table Biaxial Test with Broad Band Required Response Spectrum

3.1 Max Input Acceleration (Response is binary operability)

Electrical Penetrations
Fuses
Connectors, Instrumentation
Solid State Relays
Connectors, Electrical Equipment

5 items

TYPICAL COMPONENTS IDENTIFIED IN QUESTIONNAIRE OF APPENDIX A →

Fuses
Electrical penetrations

- -

Set 12

CLASSIFICATION IDENTIFICATION ON QUESTIONNAIRES (APPENDIX A) →

1.5 Significant geometric non linearity complex and flexible

2.5 Shake Table Biaxial Test with Narrow Band Required Response Spectrum

3.2 Max Input Velocity (Response is binary operability)

Piston Actuators (Valves)
Air Diaphragm (Spring loaded) actuators
Filters (liquid)

3 items

TYPICAL COMPONENTS IDENTIFIED IN QUESTIONNAIRE OF APPENDIX A →

Piston Actuators
Air diaphragm (Spring Loaded) actuators

Set 13

CLASSIFICATION IDENTIFICATION ON QUESTIONNAIRES (APPENDIX A) →

1.9 Significant Compound Types of Non Linearity, Flexible

2.6 Shake Table Biaxial Test with Broad Band Required Response Spectrum

3.1 Max Input Acceleration (Response is Binary Operability)

Diesel Generator Unit

Battery Chargers

2 items

TYPICAL COMPONENTS IDENTIFIED IN QUESTIONNAIRE OF APPENDIX A →

Small diesel generator

Battery charger

- -

Set 14

CLASSIFICATION IDENTIFICATION ON QUESTIONNAIRES (APPENDIX A) →

1.2 Nearly Linear Flexible Simple Structure

2.1 Linear Dynamic Analysis with Required Response Spectrum

3.5 Max Response Critical Deformation

Large Motors > 50 HP

Small Motors $\leq$ 50 HP

2 items

TYPICAL COMPONENTS IDENTIFIED IN QUESTIONNAIRE OF APPENDIX A →

Electric motors

Set 15

CLASSIFICATION IDENTIFICATION ON QUESTIONNAIRES (APPENDIX A) →

1.4 Significant Geometric non linearity, simple, flexible

2.4 Non Linear Dynamic Time History Analysis

3.4 Max Primary Stress

Large Tanks i.e. refueling water, condensate storage

Small Tanks

2 items

TYPICAL COMPONENTS IDENTIFIED IN QUESTIONNAIRE OF APPENDIX A →

Condensate storage tank (sloshing)

- -

Set 16

CLASSIFICATION IDENTIFICATION ON QUESTIONNAIRES (APPENDIX A) →

1.4 Significant Geometric non linearity, simple, flexible

2.8 Combination In-Situ Testing and Dynamic Analysis with Required Response Spectrum

3.9 Multi-State Severity Parameter (Combination)

Mechanical Pipe Snubbers

Hydraulic Pipe Snubbers

2 items

TYPICAL COMPONENTS IDENTIFIED IN QUESTIONNAIRE OF APPENDIX A →

Pipe snubber, mechanical

Pipe snubber, hydraulic

Set 17

CLASSIFICATION IDENTIFICATION ON QUESTIONNAIRES (APPENDIX A) →

1.8 Significant Non linearity, rigid

2.6 Shake Table Biaxial Test with Broad Band Required Response Spectrum

3.1 Max Input Acceleration (Response is Binary Operability)

Instrument Tubing Connections

Circuit Breakers

2 items

TYPICAL COMPONENTS IDENTIFIED IN QUESTIONNAIRE OF APPENDIX A →

Instrument tubing connectors

Circuit breakers

- -

Set 18

CLASSIFICATION IDENTIFICATION ON QUESTIONNAIRES (APPENDIX A) →

1.9 Significant Compound Types of non-linearity, flexible

2.7 Shake Table Biaxial Test with Required PSD and duration

3.6 Fatigue Damage Test (Response is Binary Operability at an Equivalent Cycle of Input Stress Reversals, PSD and Time)

Signal Conditioner

Transmitter

2 items

TYPICAL COMPONENTS IDENTIFIED IN QUESTIONNAIRE OF APPENDIX A →

Electrical transmitter

Electrical signal conditioner

Set 19

MISCELLANEOUS

1.5	2.6	3.5	Door Assemblies
1.7	2.5	3.1	Air Conditioners
1.5	2.5	3.5	Hydraulic Actuators
1.4	2.5	3.2	H & V Dampers
1.4	2.5	3.1	Solenoid Valves
1.5	2.5	3.1	Valve Dampers
1.7	2.6	3.1	Heat Exchangers
1.9	2.4	3.9	Pipe Rupture "V" bolts
1.9	2.4	3.5	Pipe Rupture Honeycomb Pads
1.5	2.1	3.4	Spent Fuel Pool Storage Racks
1.8	2.3	3.4	Flanged Connections
1.9	2.6	3.2	Battery Cells
1.2	2.9	-	Rigid Conduit
1.3	2.5	3.1	Switches, solid state
1.3	2.3	3.3	Insulators (electrical)
1.5	2.9	-	Flexible conduit
1.4	2.9	-	Cable tie down straps
1.1	2.6	3.1	Thermocoupler
1.5	2.2	3.4	Reactor Assembly
1.1	2.8	3.5	Fuel Chambers
1.5	2.8	3.4	Fuel Assemblies
1.2	2.8	3.4	Control Rods
1.2	2.6	3.4	Core Support Plates
1.5	2.8	3.9	Control Rod Drives

24 items

APPENDIX E

QUESTIONNAIRE RAW DATA

Respondent #1

Set 5	Set 7	Set 10	Set 17
60	65	30	50
25	30	10	10
2	5	1	1
0.5	0.5	0.1	0.1
25	10	10	20
1.6	1.1	1.5	1.6

Respondent #2

Set 4	Set 13	Set 17	Set 18
50	70	80	95
5	3	5	15
0.5	.3	.5	5
.05	.03	.05	1
10	20	20	25
1.5	2	1.2	2

Respondent #3

Set 4	Set 13	Set 17	Set 18
70	80	80	80
10	5	5	5
1	0.5	0.5	0.5
0.1	.05	.05	.05
10	0	0	0
1.3	1.0	1.0	1.0

Respondent #4

Set 2	Set 3	Set 4	Set 17
70,80	80,75,70	50,60,40	50
10,20	5,7,3-5	7,3,5	10
1,3	0,2,1-3	2,0,1	5
0,1	0,0,0	0,0,0	0
0,0	0,0,0,	60,40,70	0
.9,1.2	.8,1.0,1.1	1.2,1,.8	1.5

APPENDIX E

QUESTIONNAIRE RAW DATA

Respondent #5

Set 2	Set 4	Set 9	Set 14
90	95	50	95
40	40	20	40
5	10	1	10
1	1	0.1	1
25	60	20	30
1.5	1.0	1.0	1.5

Respondent #6

Set 1	Set 3	Set 8	Set 11
99	99	99	99
70	10	20	5
40	5	10	3
20	3	5	1
50	10	10	5
1.2	1.3	1.3	1.1

Respondent #7

Set 3	Set 8	Set 11
80	60	80
2	4	1
.1	.2	.1
0	0	0
5	10	0
1.0	1.0	1.0

Respondent #8

Set 7	Set 9	Set 12	Set 16
80	85	80	70
20	30	40	40
3	2	5	5
.3	0.2	.5	.5
5	20	2	2
1.2	1.0	1.5	1.3

APPENDIX E

QUESTIONNAIRE RAW DATA

Respondent #9

Set 6	Set 11	Set 13	Set 14
50	20	15	10
5	3	2	1
2	.5	.3	.05
.1	.01	.01	.001
20	5	5	50
1.0	1.0	1.0	1.0

Respondent #10

Set 1	Set 5	Set 13	Set 18
80	95	95	95
10	30	30	30
5	5	5	5
1	1	1	1
50	75	75	75
1.5	1.3	1.3	1.3

Respondent #11

Set 1	Set 2	Set 9	Set 15
75	95	99	75
10	15	5	18
2	.1	.1	5
.1	0	0	.5
10	5	2	10
1.5	1.2	1.5	1.2

Respondent #12

Set 1	Set 4	Set 12	Set 16
85	70	60	70
15	10	20	15
3	1	5	3
2	1	3	2
35	60	2	1.6
1.5	1.2	2.0	1.5

APPENDIX E

QUESTIONNAIRE RAW DATA

Respondent #13

Set 8	Set 10	Set 12	Set 15
50	60	60	70
.1	.1	.5	10
.01	.01	.05	2
.001	.001	.005	1
0	15	0	15
1.3	1.4	1.4	1.3

APPENDIX E

QUESTIONNAIRE RAW DATA

Respondent A

Set 1
90
2
.2
.05
80
3.33

Respondent B

Set 1	Set 7	Set 14
95	90	90
40	20	20
1	10	5
.5	.5	.5
20	30	20
1.1	1.1	1.0

Respondent C

Set 1	Set 2	Set 3	Set 4	Set 5	Set 6	Set 7	Set 8	Set 9
80	95	99	99	70	95	60	99	99
10	50	50	80	60	75	40	50	50
1	1	1	40	30	10	20	1	.1
.1	.1	.1	10	10	.1	10	.1	.01
10	1	20	1	1	5	1	20	80
1.2	3.0	1.2	1.0	3.0	1.0	2.0	1.1	1.0

Set 10	Set 11	Set 12	Set 13	Set 14	Set 15	Set 16	Set 17	Set 18
95	99	90	70	90	70	90	99	70
75	50	50	50	50	65	50	50	50
50	.1	15	30	5	60	10	10	40
35	.01	1	20	1	30	.1	1	30
1	20	1	.1	20	1	1	1	.1
4.0	1.0	3.0	4.0	1.3	3.0	2.0	3.0	3.0

APPENDIX E

QUESTIONNAIRE RAW DATA

Respondent D

Set 1	Set 2	Set 4	Set 6	Set 8	Set 10	Set 12	Set 14	Set 16	Set 18
70	90	50	60	80	60	90	95	80	80
30	10	10	15	5	40	10	1	10	10
1	.1	.1	1	.05	2	.1	.05	.1	.1
.1	.01	.01	.1	.01	.5	.01	.01	.01	.01
20	30	10	10	30	20	30	20	20	20
1.5	3.0	1.2	1.2	1.5	3.0	3.0	1.3	2.0	3.0

Respondent E

Set 1	Set 3	Set 5	Set 7	Set 9	Set 11	Set 13	Set 15	Set 17
99	90	85	100	100	100	80	70	100
50	50	50	50	50	50	50	30	50
1	5	5	0	0	0	3	7	0
0	1	0	0	0	0	0	2	0
10	10	7	5	5	5	8	5	5
1.2	1.2	1.3	1.2	1.15	1.15	1.4	1.3	1.3

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16. ABSTRACT (200 words or less)

This project is directed toward a portion of the Seismic Safety Margins Research Program which includes one link in the seismic methodology chain. The link addressed here is the structural subsystem dynamic response which consists of those components and systems whose behavior is often determined decoupled from the major structural response. Typically the mathematical model utilized for the major structural response will include only the mass effects of the subsystem and the main model is used to produce the support motion inputs for subsystem seismic qualification

The main questions addressed in this report have to do with the seismic response uncertainty of safety-related components or equipment whose seismic qualification is performed by a) analysis, b) tests, or c) combinations of analysis and tests, and where the seismic input is assumed to have no uncertainty. In order to strike a balance between a generic treatment of subsystem response uncertainty and a more specific treatment of detail problems which are unique to certain pieces of equipment, a typical LWR subsystem inventory has been developed for BWR and PWR reactor systems. This inventory has been used to help classify a limited number of sets of components with common seismic uncertainty characteristics suitable for use in the Phase I SSMRP effort. The uncertainties of seismic response are quantified through judgment probability assignments by experienced NSC personnel as well as informal inputs from selected seismic nuclear experts

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